An Empirical Study of Java Bytecode Programs

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TR#04-11

Abstract

We present a study of the static structure of real Java bytecode programs. A total of 1132 Java jar-files were collected from the Internet and analyzed. In addition to simple counts (number of methods per class, number of bytecode instructions per method, etc.), structural metrics such as the complexity of control-flow and inheritance graphs were computed. We believe this study will be valuable in the design of future programming languages and virtual machine instruction sets, as well as in the efficient implementation of compilers and other language processors.

1 Introduction

In [15], Donald Knuth examined FORTRAN programs collected from printouts found in a computing center. Among other things, he found that arithmetic expressions tend to be small, which, he argued, has consequences for code-generation and optimization algorithms chosen in a compiler. Similar studies have been done for COBOL [5, 20], Pascal [10], and APL [19, 18] source code.

In this paper we report on a study on the static structure of real Java bytecode programs. Using information gathered from an automated Google search, we collected a sample of 1132 Java programs, in the form of jar-files (collections of Java class files). The static structure of these programs was analyzed automatically using SandMark, a tool which, among other things, performs static analysis of Java bytecode.

It is our hope that the information gathered and presented here will be of use in a variety of settings.

For example, information about the structure of real programs in one language can be used to design future languages in the same family. One example is the `finally` clause of Java exception handlers. Special instructions (`jsr` and `ret`) were added to Java bytecode to handle this construct efficiently. These instructions turn out to be a major source of complexity for the Java verifier [21]. If, instead, the Java bytecode designers had known (from a study of MODULA-3 programs, for example) that the `finally` clause is very unusual in real programs, they may have elected to keep `jsr`/`ret` out of the instruction set. This would have simplified the Java bytecode verifier while imposing little overhead on typical programs[1].

There are many types of tools that operate on programs. Compilers are an obvious example, but there are many software engineering tools which transform programs in order to improve on their structure, readability, modifiability, etc. Such language processors can benefit from knowing typical and extreme counts of various aspects of real programs. For example, in our study we have found that while, on average, a Java class file has 9.0 methods, in the extreme case we found a class with 570 methods. This information can be used to select appropriate data structures, algorithms, and memory allocation strategies.

Our own research is focused on the protection of software from piracy, tampering, and reverse engineering, using code obfuscation and software watermarking [8]. Code obfuscation attempts to introduce confusion in a program to slow down an adversary's attempts at reverse engineering it. Software watermarking inserts a copyright notice

[1] The `finally` clause can be implemented by copying code.

or customer identification number into a program to allow the owner to assert their intellectual property rights. An important aspect of these techniques is *stealth*. For example, a software watermarking algorithm should not embed a mark by inserting code that is highly unusual, since that would make it easy to locate and remove. Our goal is to use the information gathered in this study to develop evaluation models for the stealth of software protection algorithms.

The remainder of this paper is structured as follows. In Section 2 we describe how our statistics were gathered. In Section 3 we give a brief overview of Java bytecode. In Sections 4, 5, 6, and 7, we present application-level, class-level, method-level, and instruction-level statistics, respectively. In Section 8 we discuss related work, and in Section 9 we summarize our findings.

2 Experimental Methodology

Table 1 shows some statistics of the applications that were gathered. Figure 1 shows an overview of how our statistics were collected.

To obtain a suitably random set of sample data, we queried the Google search engine using the key-phrase “`"index of" jar`”. This query was designed to find web-pages that display server directory listings that contain files with the extension `.jar`. In the resulting HTML pages we searched for any `<A>` tag whose `HREF` attribute designated a jar-file. These files were then downloaded.

The initial collection of jar-files numbered in excess of 2000. An initial analysis discarded any files that contained no Java classes, or were structurally invalid. Static statistics were next gathered using the SandMark tool.

SandMark [7] is a tool developed to aid in the study of software-based software protection techniques. The tool is implemented in Java and operates on Java bytecode. Included in SandMark are algorithms for code obfuscation, software watermarking, and software birthmarking. To aid in the development of new algorithms and as a means to study the effectiveness of these algorithms a variety of static analysis techniques are included. Examples of such techniques are class hierarchy, control-flow, and call graphs; def-use and liveness analysis; stack simulation; forward and backward slicing; various bytecode diffing algorithms; a bytecode viewer; and a variety of software complexity metrics.

Not all well-formed jar-files could be completely analyzed. In most cases this was because the jar-file was not self-contained, i.e. it referenced classes not in the jar, or in the Java standard library. Missing class files prevents the class hierarchy from being constructed, for example. In these cases we still computed as much statistics as possible. For example, while an incomplete class hierarchy prevented us from gathering accurate statistics of class inheritance depth, it still allowed us to gather control flow graph statistics. Our SandMark tool is also not perfect. In particular, it is known to build erroneous control-flow graphs (CFGs) for methods with complex subroutine structure (combinations of the `jsr` and `ret` instructions used for Java’s `finally`-clause). There are few such CFGs in our sample set, so this problem is unlikely to adversely affect our data.

Because of our random sampling of jar-files from the Internet, the collection is somewhat idiosyncratic. We assume that any two jar-files with the same name are in fact the same program, and keep only one. However, we kept those files whose names indicated that they were different versions of the same program, as shown by the `OligoWiz`-files in Figure 1. Most likely, these files are very similar and may contain methods that are identical between versions. It is reasonable to assume that such redundancy will have somewhat skewed our results. An alternative strategy might have been to guess (based on the file name) which files are versions of the same program, and keep only the higher-numbered file. A less random sampling of programs could also have been collected from well-known repositories of Java code, such as `sourceforge.net`.

Giving an informative presentation of this type of data turns out to be difficult. In many applications we will only be interested in *typical* values (such as *mode* or *mean*) or extreme values (such as *min* and *max*). Such values can easily by presented in tabular form. However, we would also like to be able to quickly get a general “feel” for the behavior of the data, and this is best presented in a visual form. The visualization is complicated by the fact that most of our data has sharp “spikes” and long “tails”. That is, one or a few (typically small) values are very common, but there are a small number of large outliers which by themselves are also interesting. This can be seen, for example, in Figure 29(b), which shows that out of the 801117 methods in our data, 99% have fewer than 2 subroutines but one method has 29 subroutines.

We have chosen to visualize much of our data using binned bar-graphs where extremely tall bars are truncated to allow small values to be visualized. For example, consider the graph below which shows the number of constants in the constant pool of the Java applications we studied:

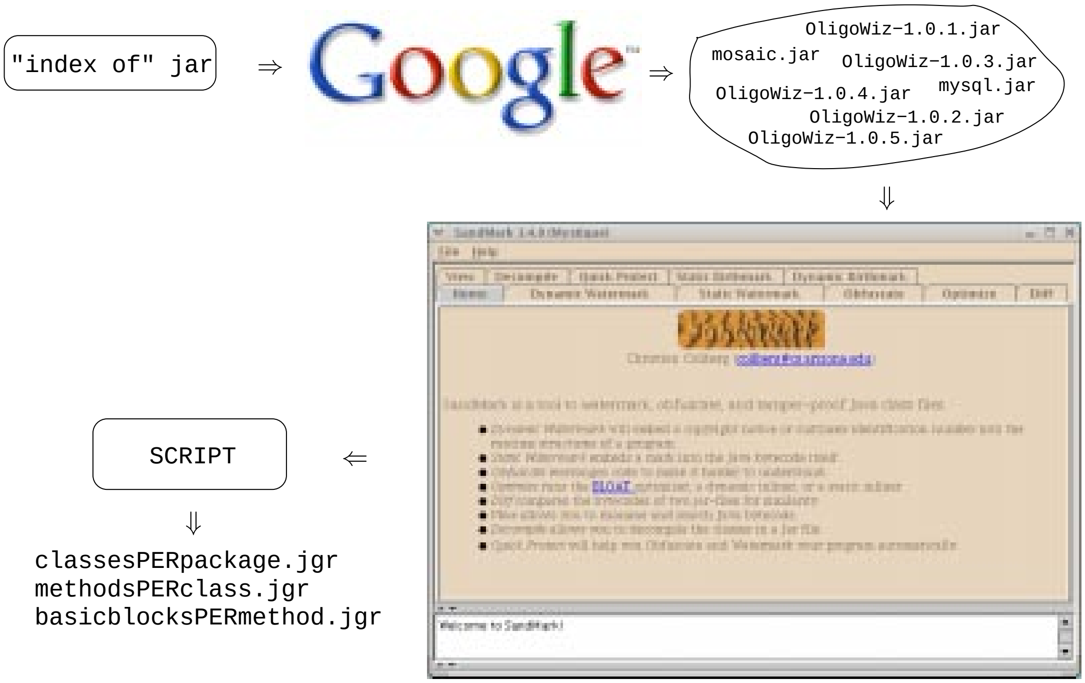
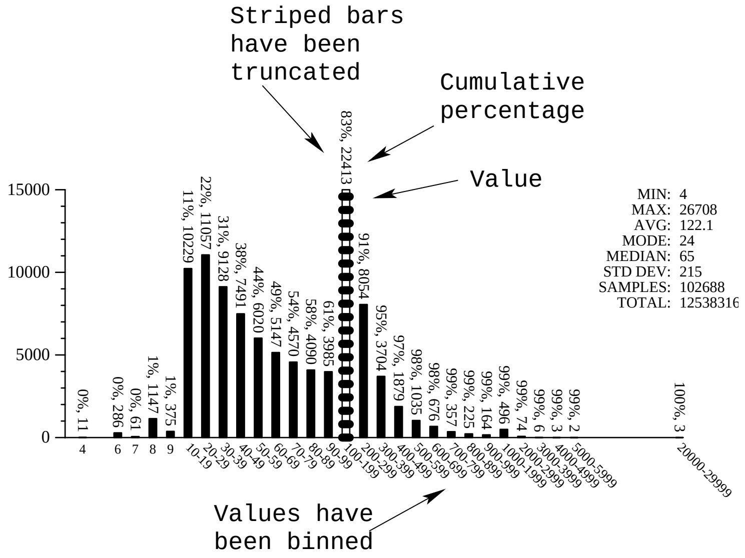


Figure 1: Overview of how our statistics were gathered.

Table 1: Collected jar-file statistics.

measure	count
total number of jar-files	1132
total size of jar-files (MB)	198945317
total number of class files	102688
total number of packages	7682
total number of classes	90500
total number of interfaces	12188
total number of constant pool entries	12538316
total number of methods	874115
total number of fields	422491
total number of instructions	26597868



Most of our graphs will have the same structure. Along the X-axis we show the bins into which our data has been classified. On top of each bar the actual count and cumulative percentage are shown. Very tall bars are truncated and shown striped. In a separate table to the top right of the graph we show the total number of data points, the minimum, maximum, and average X-values, the *mode*[2], the *median* (the middle value), and the standard deviation. The `SAMPLES` values is the total number of items inspected for the given statistic, and the `TOTAL` value is the total number of sub-items counted. For example; in the above graph, the `SAMPLES` value will be the number of classes analyzed and the `TOTAL` value will be the sum of all the constant pool entries over all the classes analyzed. The `TOTAL` value is only included where appropriate. The `FAILED` value gives the number of unsuccessful measurements, when appropriate.

3 The Structure of Java Bytecode Programs

A Java application consists of a collection of classes and interfaces. Each class or interface is compiled into a *class file*. A program consists of a number of class files which are collected together into a *jar-file*. A jar-file is directly executable by a Java virtual machine interpreter. The Java class file stores all necessary data regarding the class. There is a symbol table (called the *Constant Pool*) which stores strings, large literal integers and floats, and names and types and of all fields and methods. Each method is compiled to Java bytecode, a stack-based virtual machine instruction set. Figure 2 shows the structure of the Java class file format. The JVM is defined by Lindholm and Yellin [16].

The Java bytecodes can manipulate data in several formats: integers (32-bits), longs (64-bits), floats (32-bits), doubles (64-bits), shorts (16-bits), bytes (8-bits), booleans (1-bit), chars (16-bit Unicode), object references (32-bit pointers), and arrays. The boolean, byte, char, and short types are compiled down into integers.

Bytecode instructions are variable width. Simple instructions such as `iadd` (integer addition) are one byte wide, while some instructions (such as `tableswitch`) can be multiple bytes. Each method can have up to 65536 local variables and formal parameters, called *slots*. The bytecodes reference slots by number. For example, the instruction `'iload_3'` pushes the third local variable onto the stack. In order to access high-numbered slots, a special `wide` instruction can be used to modify load and store instructions to use 16-bit indexes. The Java execution stack is 32-bits wide. Longs and doubles take up two stack entries and two slot numbers.

Local variable slots are untyped. In fact, a particular slot can hold different types of data at different locations in a method. However, regardless of how execution reaches a given location in the method, the type of data stored in a particular slot at that location will always be the same. A static analysis known as a *stack simulation* can compute slot types without executing a method.

Some bytecodes reference data from the class' constant pool, for example to push large constants or to invoke methods. Constant pool references are 8 or 16 bits long. To push a reference to a literal string with constant pool

[2] The mode is the most frequently occurring value. This is often — but because of binning not always — the tallest bar of the graph.

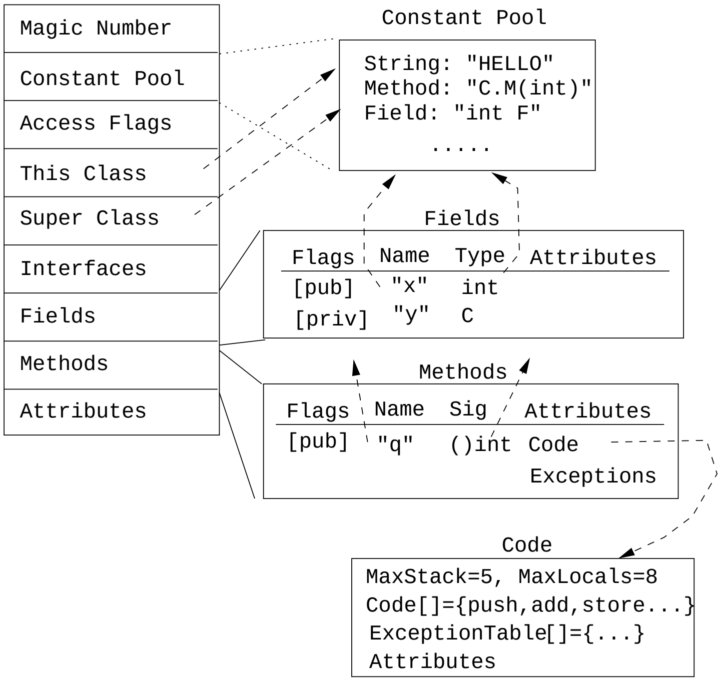


Figure 2: A view of the Java class file format.

number 4567, the compiler would issue the instruction `'ldc_w 4567'`. If the constant pool number instead fits in a byte (such as 123), the shorter instruction `'ldc 123'` would suffice.

Some information is stored in *attributes* in the class file. This includes exception table ranges, and (for debugging) line-number ranges and local variable names.

Tables 3 through 6 give an overview of the Java virtual machine instruction set. Table 2 explains the notation used.

4 Program-Level Statistics

In this and the following three sections we will present the data collected about applications (this section), classes (Section 5), methods (Section 6), and instructions (Section 7).

Figures 3, 4, 5, and 6 visualize application-level data about the programs we gathered.

4.1 Packages

Classes in Java are optionally organized into a hierarchy of *packages*. For example, Java's `String` class is in the package `java.lang`, and can be referred to as `java.lang.String`. As can be seen from Figure 3(a), many Java programs put all classes into the same package. In fact, half of the 1132 applications we gathered have 3 or fewer packages, and only 4 have 50 or more.

A package α is counted if there exists some class β such that the fully-qualified classname of β is $\alpha.\beta$. Thus if an application has classes *java.pack1.Class1* and *java.pack2.Class2* then *java.pack1* and *java.pack2* would be counted, but *java* would not. Also, the default or "null" package is counted exactly once, if there is a class in that package.

Figure 4(a) shows that while a small number of programs have packages with hundreds of classes, the typical package will have only one, and the average is about 11.8.

Packages can be nested inside of other packages, allowing for the easy creation of unique names. While it is possible to create a package hierarchy of arbitrary depth, Figure 3(b) shows that the maximum depth for an application is 8, with an average depth of 3.9.

Table 2: Notation used to refer to data values in the bytecode.

notation	**explanation**
B	An 8-bit integer value.
S	A 16-bit integer value.
L	A 32-bit integer value.
C_b	An 8-bit constant pool index.
C_s	A 16-bit constant pool index.
F_b	An 8-bit local variable index.
F_s	A 16-bit local variable index.
$C[i]$	The i:th constant pool entry.
$V[i]$	The i:th variable/formal parameter in the current method.

Table 3: The first 87 Java bytecode instructions.

Opcode	Mnemonic	Args	Stack	Description
0	nop		$[] \Rightarrow []$	
1	aconst_null		$[] \Rightarrow [\text{null}]$	Push null object
2	iconst_m1		$[] \Rightarrow [\text{-1}]$	Push -1
3…8	iconst_n		$[] \Rightarrow [n]$	Push integer constant $n, 0 \leq n \leq 5$
9…10	lconst_n		$[] \Rightarrow [n]$	Push long constant $n, 0 \leq n \leq 1$
11…13	fconst_n		$[] \Rightarrow [n]$	Push float constant $n, 0 \leq n \leq 2$
14…15	dconst_n		$[] \Rightarrow [n]$	Push double constant $n, 0 \leq n \leq 1$
16	bipush	n:B	$[] \Rightarrow [n]$	Push 1-byte signed integer
17	sipush	n:S	$[] \Rightarrow [n]$	Push 2-byte signed integer
18	ldc	n:C_b	$[] \Rightarrow [C[n]]$	Push item from constant pool
19	ldc_w	n:C_s	$[] \Rightarrow [C[n]]$	Push item from constant pool
20	ldc2_w	n:C_s	$[] \Rightarrow [C[n]]$	Push long/double from constant pool
21…25	Xload	n:F_b	$[] \Rightarrow [V[n]]$	$X \in$\{i,l,f,d,a\}, Load int, long, float, double, object from local var.
26…29	iload_n		$[] \Rightarrow [V[n]]$	Load local integer var $n, 0 \leq n \leq 3$
30…33	lload_n		$[] \Rightarrow [V[n]]$	Load local long var $n, 0 \leq n \leq 3$
34…37	fload_n		$[] \Rightarrow [V[n]]$	Load local float var $n, 0 \leq n \leq 3$
38…41	dload_n		$[] \Rightarrow [V[n]]$	Load local double var $n, 0 \leq n \leq 3$
42…45	aload_n		$[] \Rightarrow [V[n]]$	Load local object var $n, 0 \leq n \leq 3$
46…53	Xload		$[A, I] \Rightarrow [V]$	$X \in$\{ia,la,fa,da,aa,ba,ca,sa\}. Push the value V (an int, long, etc.) stored at index I of array A.
54…58	Xstore	n:F_b	$[V[n]] \Rightarrow []$	$X \in$\{i,l,f,d,a\}, Store int, long, float, double, object to local var.
59…62	istore_n		$[V[n]] \Rightarrow []$	Store to local integer var $n, 0 \leq n \leq 3$
63…66	lstore_n		$[V[n]] \Rightarrow []$	Store to local long var $n, 0 \leq n \leq 3$
67…70	fstore_n		$[V[n]] \Rightarrow []$	Store to local float var $n, 0 \leq n \leq 3$
71…74	dstore_n		$[V[n]] \Rightarrow []$	Store to local double var $n, 0 \leq n \leq 3$
75…78	astore_n		$[V[n]] \Rightarrow []$	Store to local object var $n, 0 \leq n \leq 3$
79…86	Xstore		$[A, I, V] \Rightarrow []$	$X \in$\{ia,la,fa,da,aa,ba,ca,sa\}. Store the value V (an int, long, etc.) at index I of array A.

Table 4: Java bytecode instructions.

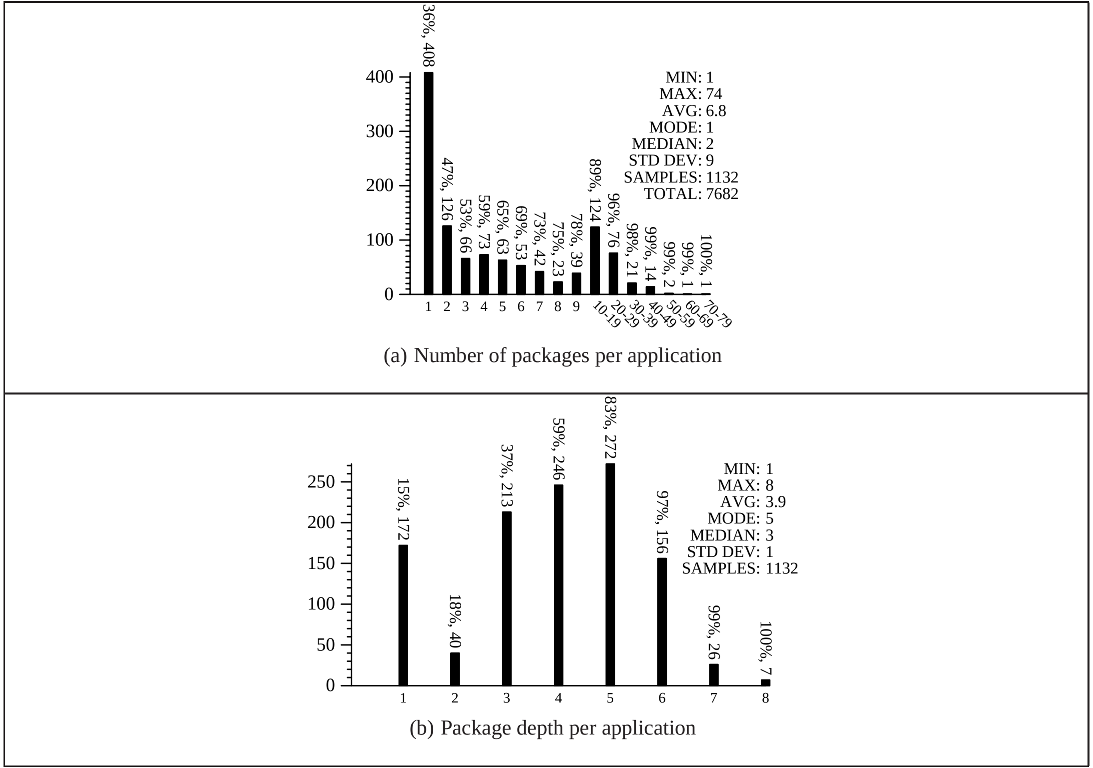
Opcode	Mnemonic	Args	Stack	Description
87	pop		$[A] \Rightarrow []$	Pop top of stack.
88	pop2		$[A,B] \Rightarrow []$	Pop 2 elements.
89	dup		$[V] \Rightarrow [V,V]$	Duplicate top of stack.
90	dup_x1		$[B,V] \Rightarrow [V,B,V]$	
91	dup_x2		$[B,C,V] \Rightarrow [V,B,C,V]$	
92	dup2		$[V,W] \Rightarrow [V,W,V,W]$	
93	dup2_x1		$[A,V,W] \Rightarrow [V,W,A,V,W]$	
94	dup2_x2		$[A,B,V,W] \Rightarrow [V,W,A,B,V,W]$	
95	swap		$[A,B] \Rightarrow [B,A]$	Swap top stack elements.
96…99	Xadd		$[A,B] \Rightarrow [R]$	$X \in${i,l,d,f}. $R = A + B$
100…103	Xsub		$[A,B] \Rightarrow [R]$	$X \in${i,l,d,f}. $R = A - B$
104…107	Xmul		$[A,B] \Rightarrow [R]$	$X \in${i,l,d,f}. $R = A * B$
108…111	Xdiv		$[A,B] \Rightarrow [R]$	$X \in${i,l,d,f}. $R = A/B$
112…115	Xrem		$[A,B] \Rightarrow [R]$	$X \in${i,l,d,f}. $R = A\%B$
116…119	Xneg		$[A] \Rightarrow [R]$	$X \in${i,l,d,f}. $R = -A$
120…121	Xshl		$[A,B] \Rightarrow [R]$	$X \in${i,l}. $R = A << B$
122…123	Xshr		$[A,B] \Rightarrow [R]$	$X \in${i,l}. $R = A >> B$
124…125	Xushr		$[A,B] \Rightarrow [R]$	$X \in${i,l}. $R = A >>> B$
126…127	$X$and		$[A,B] \Rightarrow [R]$	$X \in${i,l}. $R = A \& B$
128…129	Xor		$[A,B] \Rightarrow [R]$	$X \in${i,l}. $R = A \mid B$
130…131	Xxor		$[A,B] \Rightarrow [R]$	$X \in${i,l}. $R = A\,\mathtt{xor}\,B$
132	iinc	$V{:}F_b,B{:}B$	$[] \Rightarrow []$	$V += B$
133…144	$X$2$Y$		$[F] \Rightarrow [T]$	Convert F from type X to T of type Y. $X \in${i,l,f,d}, $Y \in${i,l,f,d}.
145…147	i2X		$[F] \Rightarrow [T]$	$X \in${b,c,s}. Convert integer F to byte, char, or short.
148	lcmp		$[A,B] \Rightarrow [V]$	Compare long values. $A > B \Rightarrow V = 1$, $A < B \Rightarrow V = -1$, $A = B \Rightarrow V = 0$.
149,151	Xcmpl		$[A,B] \Rightarrow [V]$	Compare float or double values. $X \in${f,d}. $A > B \Rightarrow V = 1$, $A < B \Rightarrow V = -1$, $A = B \Rightarrow V = 0$. $A = \mathtt{NaN} \vee B = \mathtt{NaN} \Rightarrow V = -1$
150,152	Xcmpg		$[A,B] \Rightarrow [V]$	Compare float or double values. $X \in${f,d}. $A > B \Rightarrow V = 1$, $A < B \Rightarrow V = -1$, $A = B \Rightarrow V = 0$. $A = \mathtt{NaN} \vee B = \mathtt{NaN} \Rightarrow V = 1$
153…158	if◇	$L{:}S$	$[A] \Rightarrow []$	◇={eq,ne,lt,ge,gt,le}. If $A \diamond 0$ goto $L + \mathtt{pc}$.
159…164	if_icmp◇	$L{:}S$	$[A,B] \Rightarrow []$	◇={eq,ne,lt,ge,gt,le}. If $A \diamond B$ goto $L + \mathtt{pc}$.
165…166	if_acmp◇	$L{:}S$	$[A,B] \Rightarrow []$	◇={eq,ne}. A,B are object refs. If $A \diamond B$ goto $L + \mathtt{pc}$.
167	goto	$I{:}S$	$[] \Rightarrow []$	Jump to $I + \mathtt{pc}$.
168	jsr	$I{:}S$	$[] \Rightarrow [A]$	Jump subroutine to instruction $I + \mathtt{pc}$. $A =$ the address of the instruction after the jsr.
169	ret	$L{:}F_b$	$[] \Rightarrow []$	Return from subroutine. Address in local var L.

Table 5: Java bytecode instructions.

Opcode	Mnemonic	Args	Stack
170	`tableswitch`	D:L,l,h:L,o^{h-l+1}	$[K] \Rightarrow []$
	JuLongDescrmp through the K:th offset. Else goto D.		
171	`lookupswitch`	D:L,n:L,$(m,o)^n$	$[K] \Rightarrow []$
	If, for one of the (m,o) pairs, $K = m$, then goto o. Else goto D.		
172…176	X`return`		$[V] \Rightarrow []$
	$X \in$ {i,f,l,d,a}. Return V.		
177	`return`		$[] \Rightarrow []$
	Return from void method.		
178	`getstatic`	F:C_s	$[] \Rightarrow [V]$
	Push value V of static field F.		
179	`putstatic`	F:C_s	$[V] \Rightarrow []$
	Store value V into static field F.		
180	`getfield`	F:C_s	$[R] \Rightarrow [V]$
	Push value V of field F in object R.		
181	`putfield`	F:C_s	$[R,V] \Rightarrow []$
	Store value V into field F of object R.		
182	`invokevirtual`	P:C_s	$[R,A_1,A_2,\ldots] \Rightarrow []$
	Call virtual menthod P, with arguments $A_1 \cdots A_n$, through object reference R.		
183	`invokespecial`	P:C_s	$[R,A_1,A_2,\ldots] \Rightarrow []$
	Call private/init/superclass menthod P, with arguments $A_1 \cdots A_n$, through object reference R.		
184	`invokestatic`	P:C_s	$[A_1,A_2,\ldots] \Rightarrow []$
	Call static menthod P with arguments $A_1 \cdots A_n$.		
185	`invokeinterface`	P:C_s,n:S	$[R,A_1,A_2,\ldots] \Rightarrow []$
	Call interface menthod P, with n arguments $A_1 \cdots A_n$, through object reference R.		
187	`new`	T:C_s	$[] \Rightarrow [R]$
	Create a new object R of type T.		
188	`newarray`	T:B	$[C] \Rightarrow [R]$
	Allocate new array R, element type T, C elements long.		
189	`anewarray`	T:C_s	$[C] \Rightarrow [A]$
	Allocate new array A of reference types, element type T, C elements long.		
190	`arraylength`		$[A] \Rightarrow [L]$
	Determines the length L of array A.		
191	`athrow`		$[R] \Rightarrow [?]$
	Throw exception.		
192	`checkcast`	C:C_s	$[R] \Rightarrow [R]$
	Ensures that R is of type C.		
193	`instanceof`	C:C_s	$[R] \Rightarrow [V]$
	Push 1 if object R is an instance of class C, else push 0.		
194	`monitorenter`		$[R] \Rightarrow []$
	Get lock for object R.		
195	`monitorexit`		$[R] \Rightarrow []$
	Release lock for object R.		

Table 6: Java bytecode instructions.

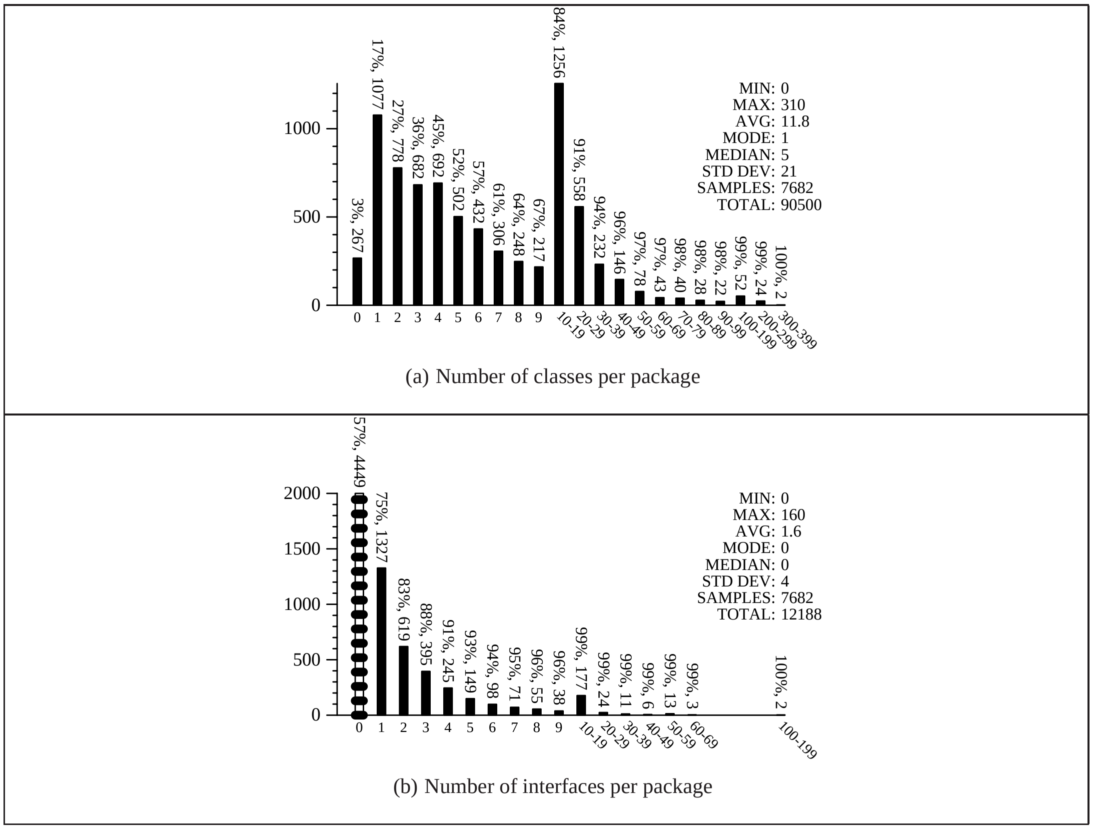
Opcode	Mnemonic	Args	Stack
196	`wide`	C:B,I:F_s	$[] \Rightarrow []$
	Perform opcode C on variable $V[I]$. C is one of the load/store instructions.		
197	`multianewarray`	T:C_s,D:C_b	$[d_1, d_2, \ldots] \Rightarrow [R]$
	Create new D-dimensional multidimensional array R. $d_1, d_2, \ldots$ are the dimension sizes.		
198	`ifnull`	L:S	$[V] \Rightarrow []$
	If $V =$ `null` goto L.		
199	`ifnonnull`	L:S	$[V] \Rightarrow []$
	If $V \neq$ `null` goto L.		
200	`goto_w`	I:L	$[] \Rightarrow []$
	Goto instruction I.		
201	`jsr_w`	I:L	$[] \Rightarrow [A]$
	Jump subroutine to instruction I. A is the address of the instruction right after the jsr_w.		



(a) Number of packages per application

(b) Package depth per application

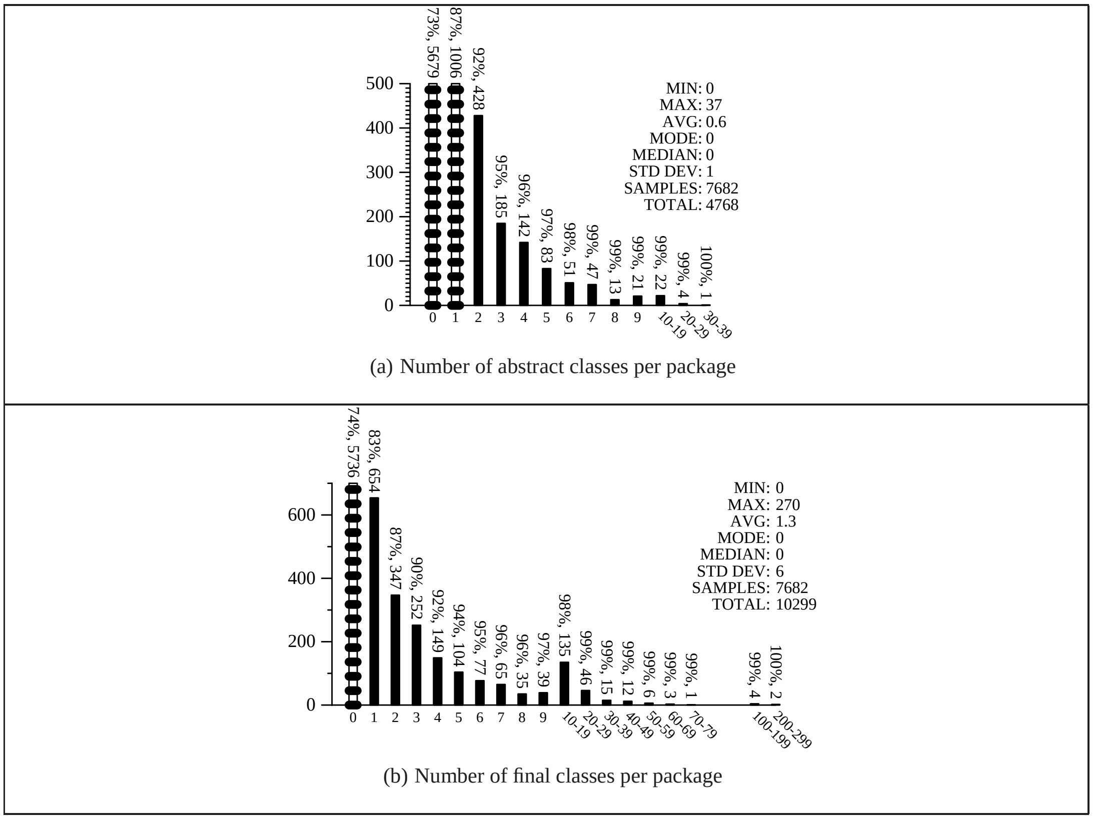
Figure 3: Program-level statistics



(a) Number of classes per package

(b) Number of interfaces per package

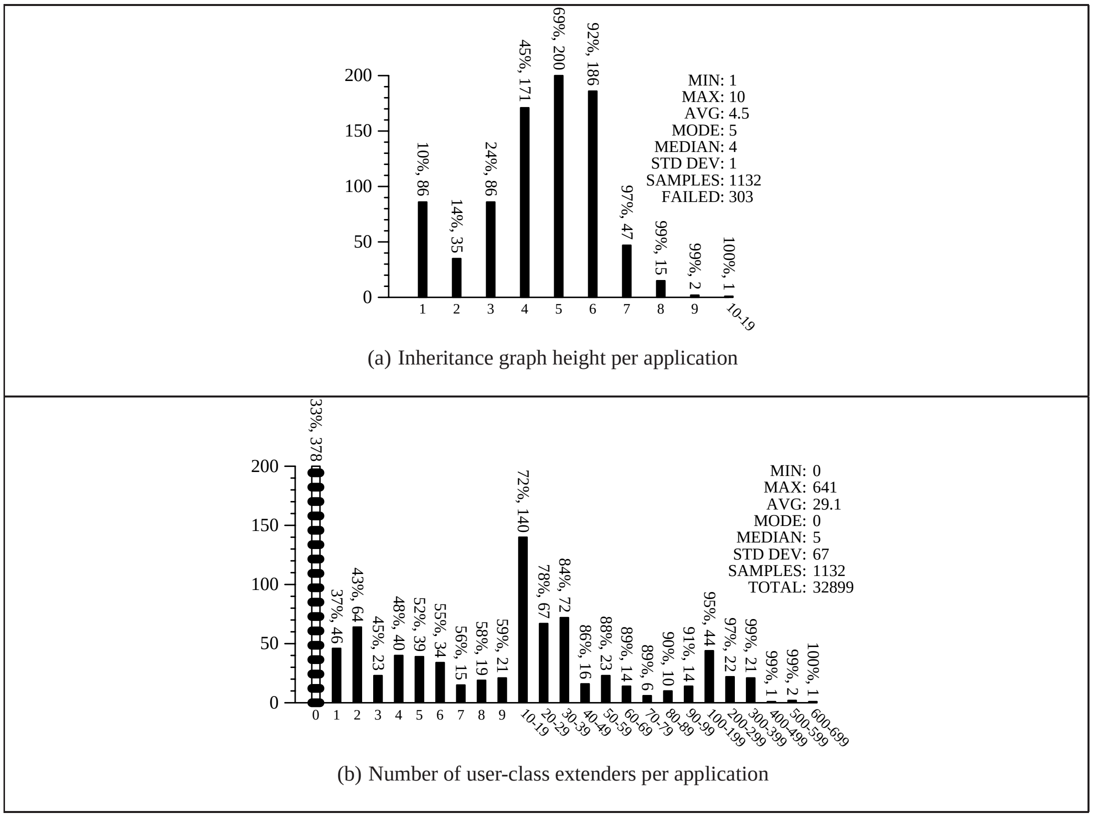
Figure 4: Program-level statistics



(a) Number of abstract classes per package

(b) Number of final classes per package

Figure 5: Program-level statistics



(a) Inheritance graph height per application

(b) Number of user-class extenders per application

Figure 6: Inheritance Graphs

A Java *interface* is a special type of class that only contains constant declarations or method signatures. A class which *implements* an interface must provide implementations of the methods. Interfaces are often used to compensate for Java's lack of multiple inheritance. Figure 4(b) show that over 70% of Java packages contain 0 or 1 interface.

4.2 Protection

A Java class can be declared as *abstract* (it serves only as a superclass to classes which actually implements its methods) or *final* (it cannot be extended). These declarations are, however, fairly unusual. Figures 5(a) and 5(b) show that over 70% of all packages contain no abstract or final classes.

4.3 Inheritance Graphs

In addition to a class implementing an interface, a class can also extend another class. In this case the subclass inherits all of the variables and methods of the class which it extends (the superclass), thus creating an inheritance relationship. An inheritance graph can be constructed to represent the superclass/subclass relationship. The *inheritance graph height* for a given application is the maximum number of superclasses that any class in the application has. This will include some but not all of the Java library classes.

Figure 6(a) shows that on average the height of an inheritance graph for an application is 4.5 and that over 90% of all applications have an inheritance graph with a height of less than 7.

It is important to note that for 303 of our applications the inheritance graph construction failed due to the jar-file not being self-contained.

Figure 6(b) shows the number of classes in each application that extend other classes in the same application. Some classes in each application *must* directly extend a Java library class (most often `java.lang.Object`), but it is interesting to note that only about 1/3 (1132/90500) extend other classes inside the same application. Table 8 shows that most of the classes in each application extend `java.lang.Object` directly.

5 Class-Level Statistics

In this section we present data regarding the top-level structure of class files. This includes the number, type/signature, and protection of fields and methods, and the class' or interface's position in the application's inheritance graph.

5.1 Fields

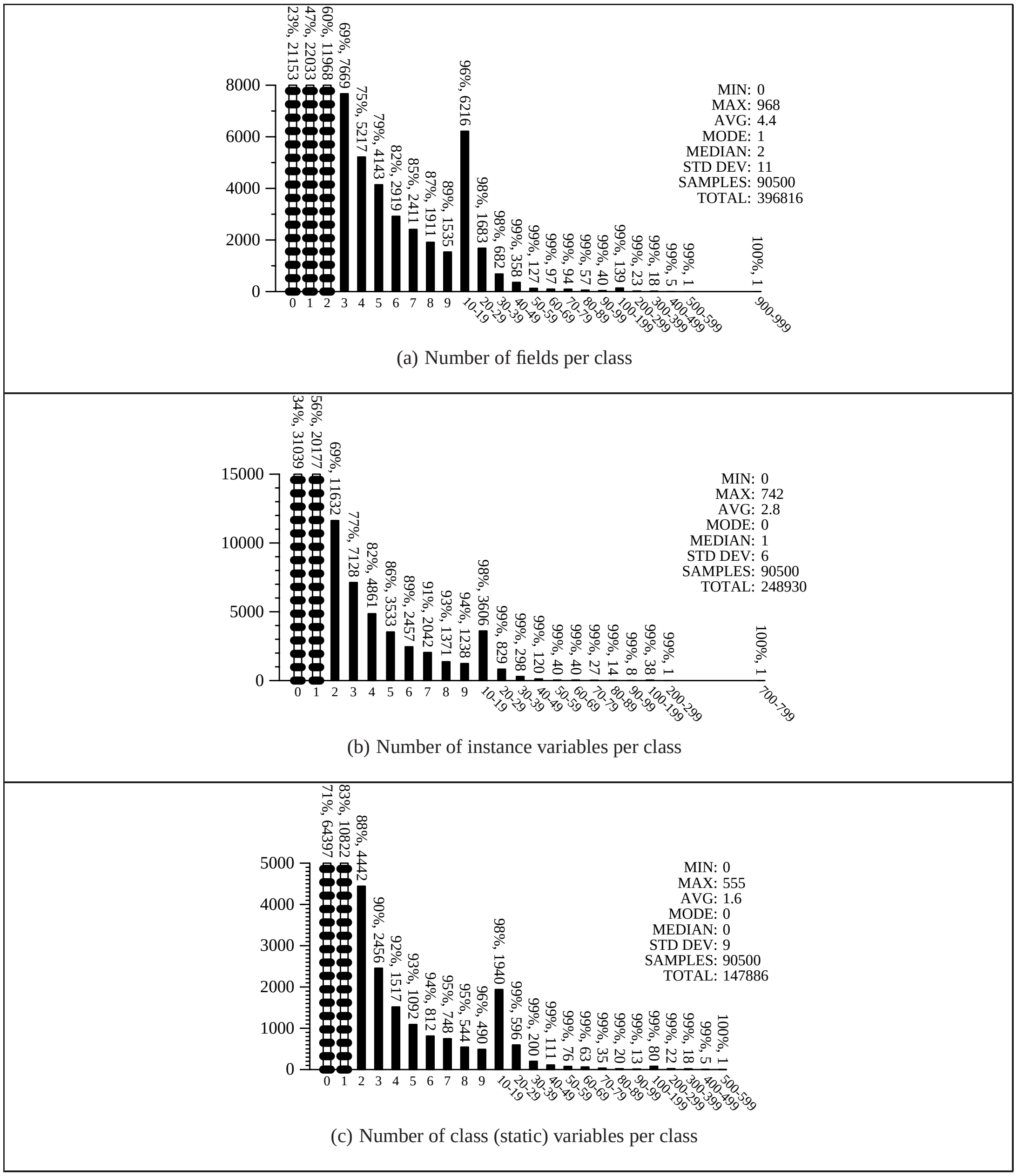
A Java class can contain data members, called *fields*. Fields are either *class variables* (they are declared `static` and only one instance exists at runtime) or *instance variables* (every instantiation of the class contains a unique copy).

Figures 7, 8, and 9 shows field statistics. In Figure 7(a) we see that 60% of all classes have two or fewer fields, but in one extreme case a class declared almost a thousand fields. Instance variables are more common than class variables. On average, a class will contain 2.8 instance variables and 1.6 class variables, and 44% of all classes have more than one instance variable but only 17% have more than one static variable. It is also more common for a class to have fields of reference types than of primitive types. On average, a class will have 1.5 fields of primitive type, but 2.6 fields of reference type.

Table 7 gives a breakdown of the declared types of fields. Only primitive types, and types exported from the Java standard library are shown. Our data also contained some user defined types with high usage counts. This is due to idiosyncrasies of our collected programs, such as a program declaring vast numbers of fields of one of its classes. Table 7 shows that the vast majority of types are `int`s, `String`s and `boolean`s. We note that, somewhat surprisingly, `java.lang.Class` (Java's notion of a class) is a frequent field type, and `double`s are more frequent than `float`s.

5.2 Constant pool

Figure 10(a) shows the number of entries in the *Constant Pool* (the class file's symbol table) per class. While small literal integers are stored directly in the bytecode, large integers as well as `String`s and real numbers are instead stored in the constant pool. Figures 11, 12, and 13 show the relative distribution of literal types.

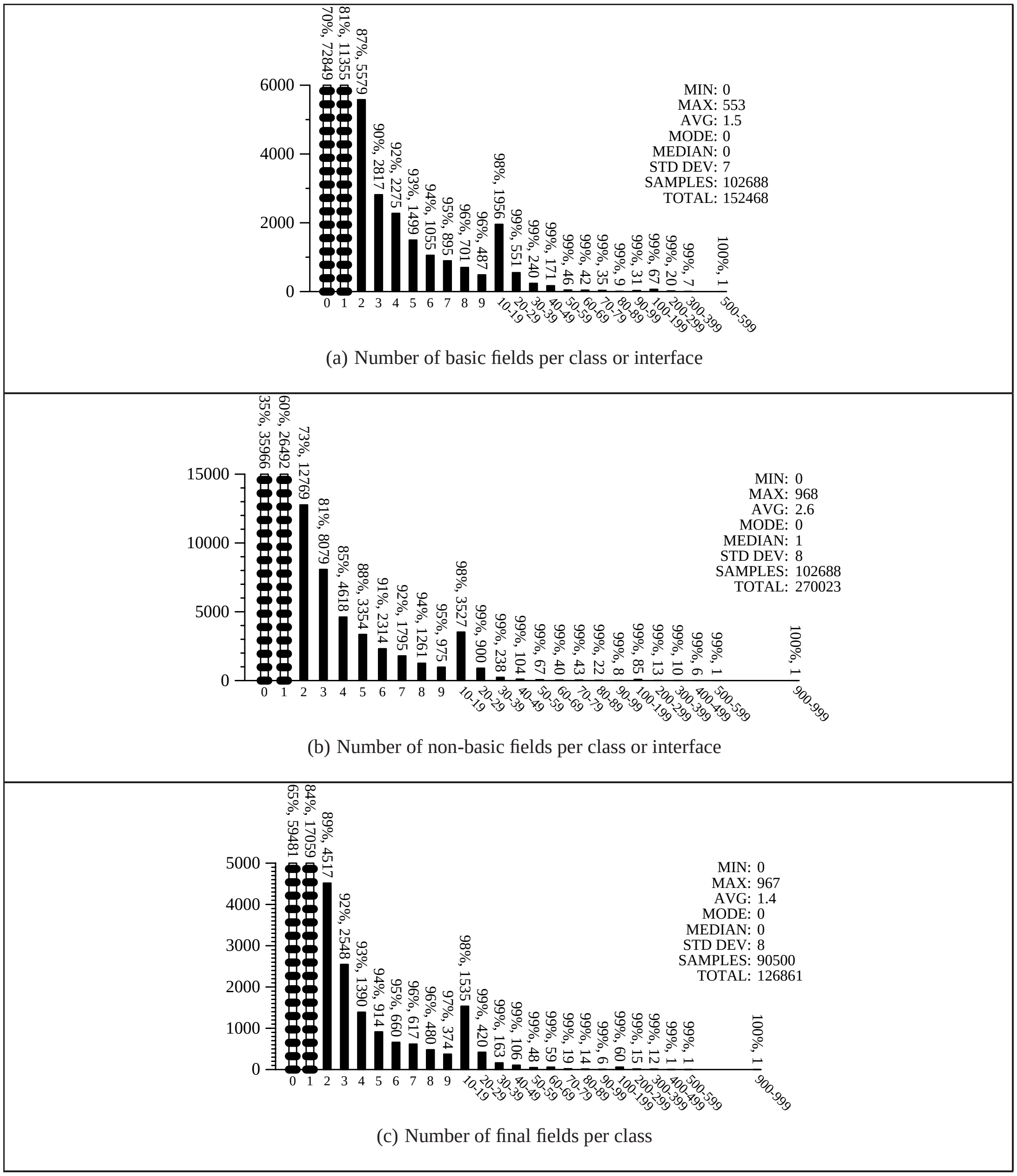


(a) Number of fields per class

(b) Number of instance variables per class

(c) Number of class (static) variables per class

Figure 7: Field declarations in classes

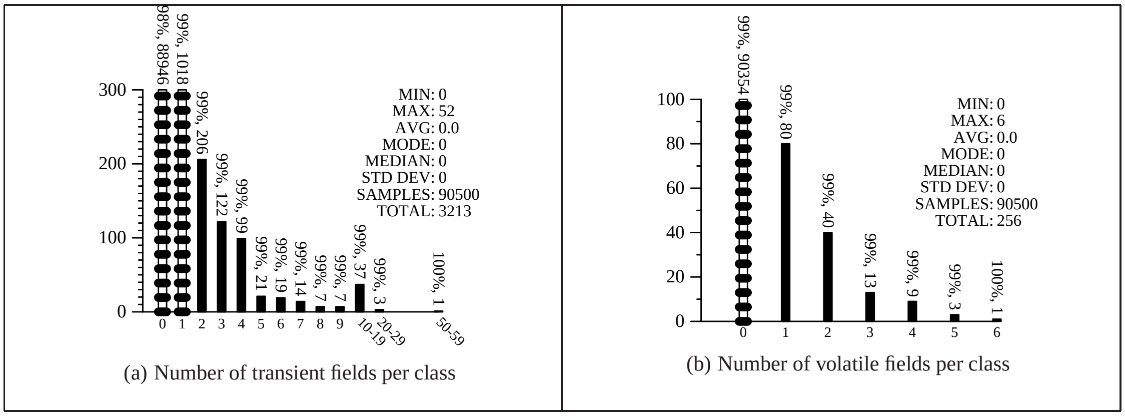


(a) Number of basic fields per class or interface

(b) Number of non-basic fields per class or interface

(c) Number of final fields per class

Figure 8: Field declarations in classes



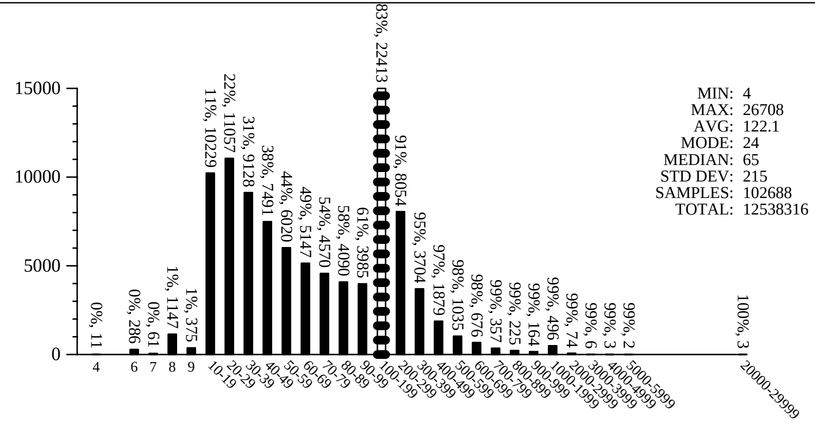
(a) Number of transient fields per class

(b) Number of volatile fields per class

Figure 9: Field declarations in classes

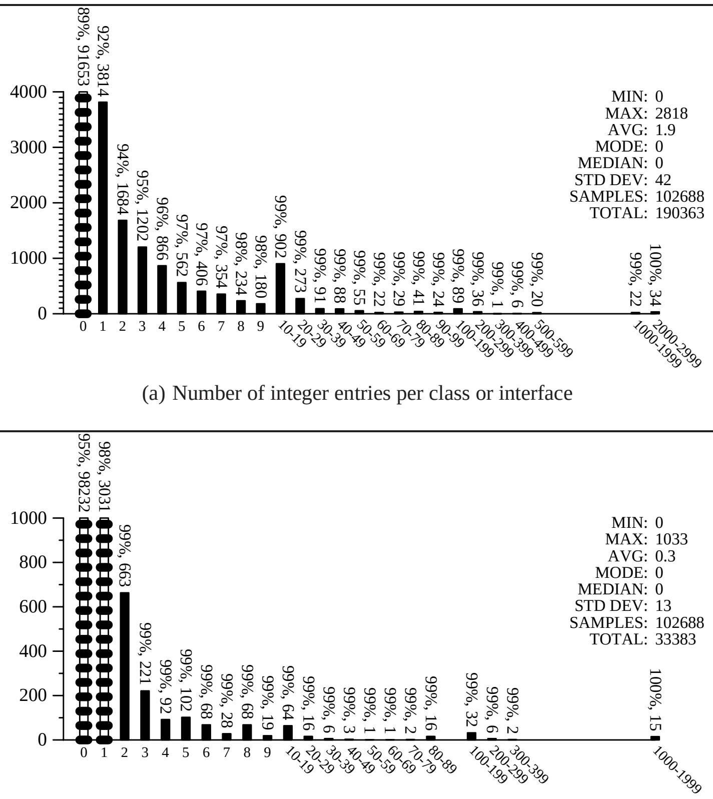
Table 7: Most common field types.

Field Type	Count	%
`int`	153861	21.8
`java.lang.String`	105787	15.0
`boolean`	44914	6.4
`java.lang.Class`	24355	3.4
`long`	16556	2.3
`java.lang.Object`	14472	2.0
`byte[]`	10229	1.4
`int[]`	8157	1.1
`java.util.Vector`	7601	1.0
`java.util.Hashtable`	7095	1.0
`short`	7048	1.0
`byte`	6464	0.9
`java.lang.String[]`	6412	0.9
`java.util.Map`	5692	0.8
`double`	5256	0.7
`java.util.List[]`	4971	0.7
`float`	3115	0.4
`java.io.File`	3019	0.4
`char[]`	2995	0.4
`java.math.BigInteger`	2782	0.3
`java.lang.StringBuffer`	2472	0.3
`java.sql.Connection`	2443	0.3
`javax.swing.JLabel`	2066	0.3
`java.util.HashMap`	2064	0.3
`java.awt.Color`	2058	0.3
`char`	1987	0.3
`java.util.ArrayList`	1748	0.2



(a) Number of constant pool entries per class or interface

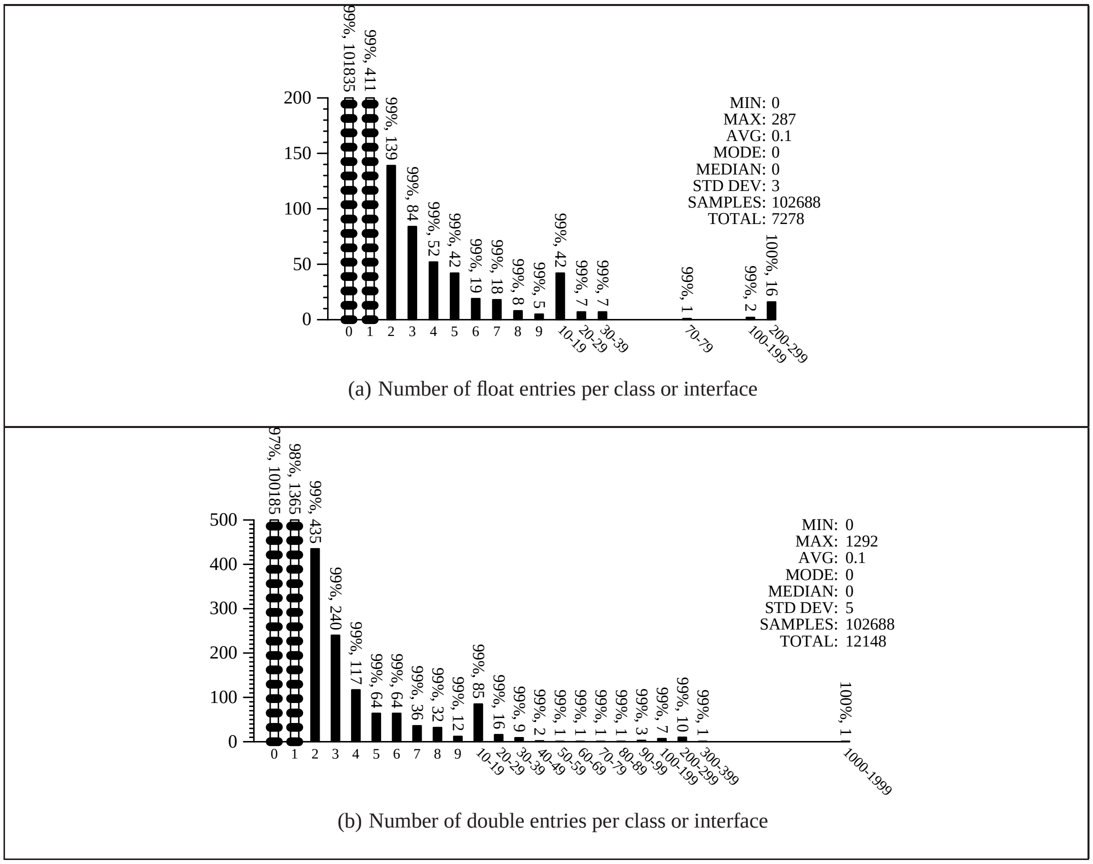
Figure 10: Constant pool entries



(a) Number of integer entries per class or interface

(b) Number of long entries per class or interface

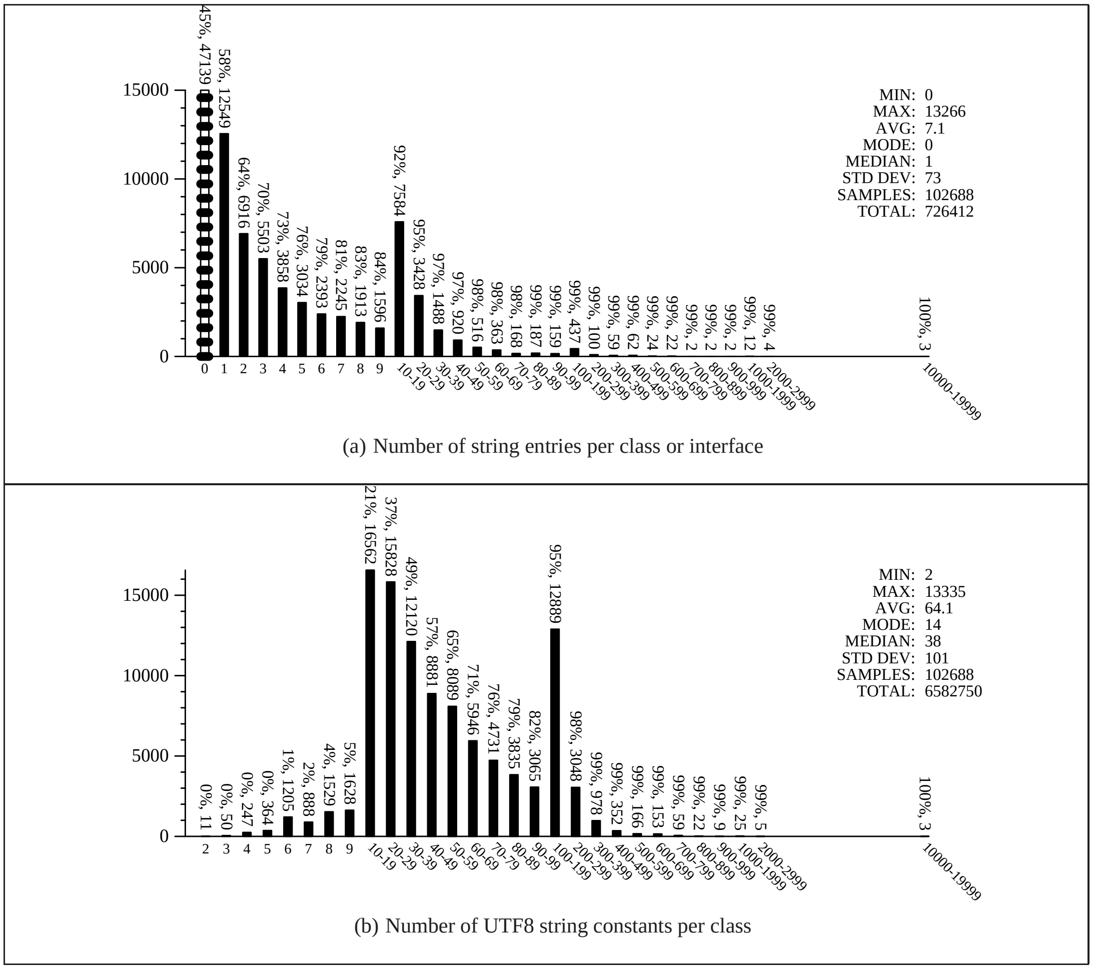
Figure 11: Literal constants in classes



(a) Number of float entries per class or interface

(b) Number of double entries per class or interface

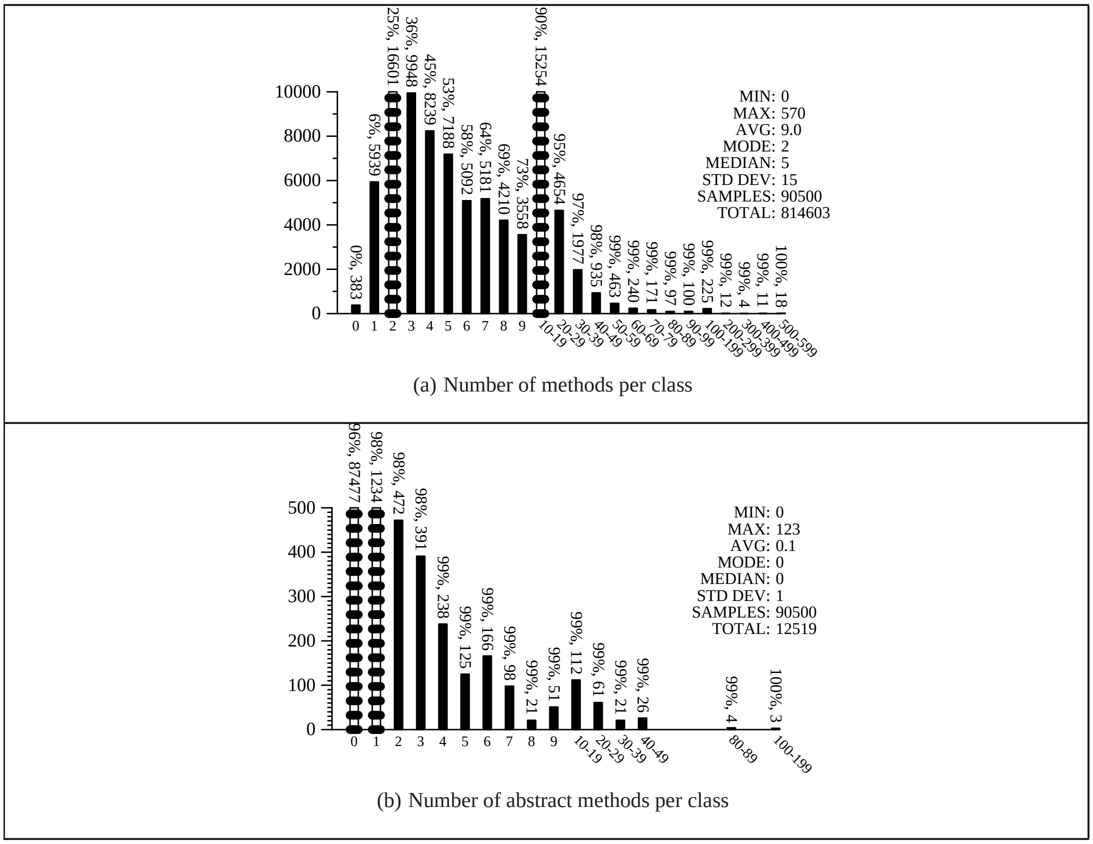
Figure 12: Literal constants in classes



(a) Number of string entries per class or interface

(b) Number of UTF8 string constants per class

Figure 13: Literal constants in classes



(a) Number of methods per class

(b) Number of abstract methods per class

Figure 14: Method declarations in classes

5.3 Methods

Figures 14, 15, and 16 give statistics of methods. Of interest is that 73% of all classes have 9 or fewer methods (Figure 14(a)), and that the vast majority of classes have no abstract or native methods (Figures 14(b) and 15(a)). Almost all classes have at least one virtual method, with an average of 7.7 methods per class (Figure 16(a)). Static methods are quite rare: 80% of all classes have at most one static method, with an average of 1.3 methods per class (Figure 15(b)).

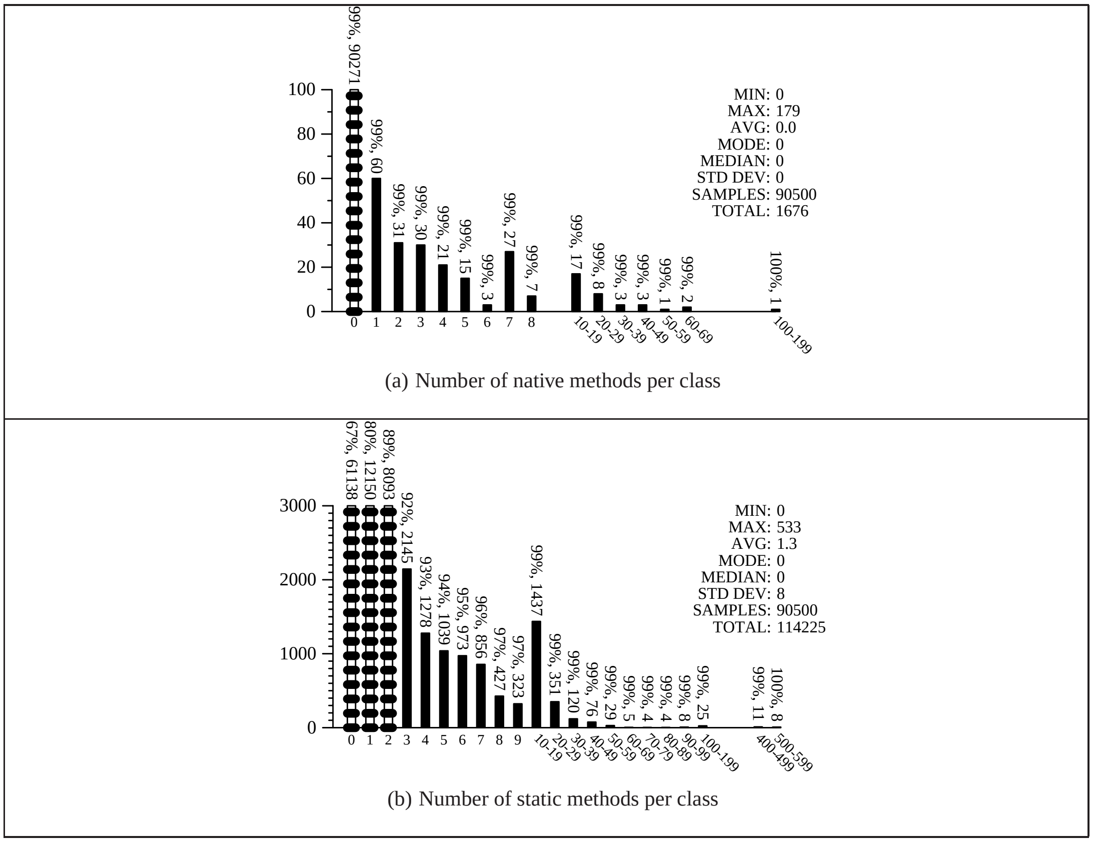
5.4 Member protection

Figures 17 and Figures 18 show the frequency of visibility restrictions of class members (fields and methods). A member can be `package private`, `private`, `protected`, or `public`. Table 18(c) summarizes the information by giving average numbers of members with a particular protection.

5.5 Inheritance

Figure 19 shows information about class inheritance. Figure 19(a) shows the number of immediate subclasses of a class, i.e. the number of classes that directly extend a particular class. Figure 19(b) shows the number of classes that directly or indirectly extend a particular class. 97% of all classes have two or fewer direct subclasses. One of the classes in our collection is extended by 187 classes. 48% of classes are at depth 1 in the inheritance graph, i.e. they extend `java.lang.Object`, the root of the inheritance graph (Figure 19(c)). The average depth of a class is low (only 2.1), although 6 of our classes are at depth 30-39. In many cases we failed to build the inheritance hierarchy due to the program containing references to classes not in the jar-file or the standard Java library.

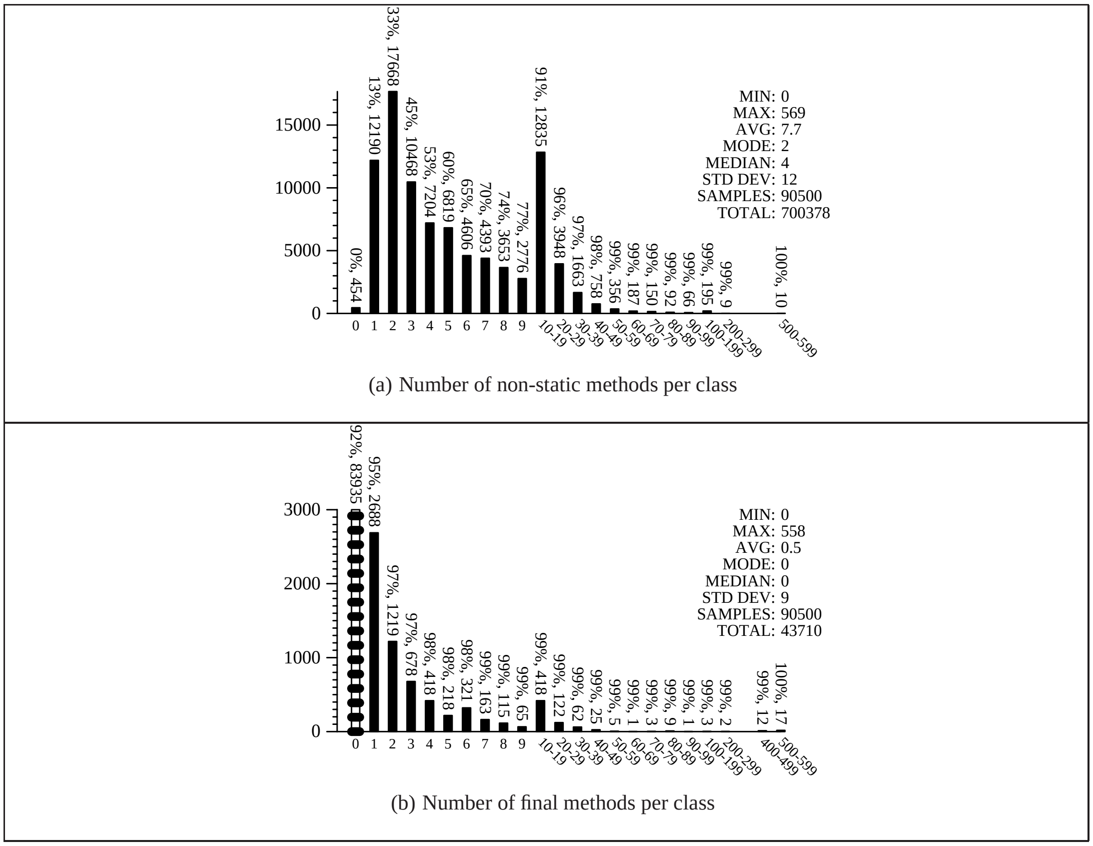
Figure 20 shows the same information for interfaces.



(a) Number of native methods per class

(b) Number of static methods per class

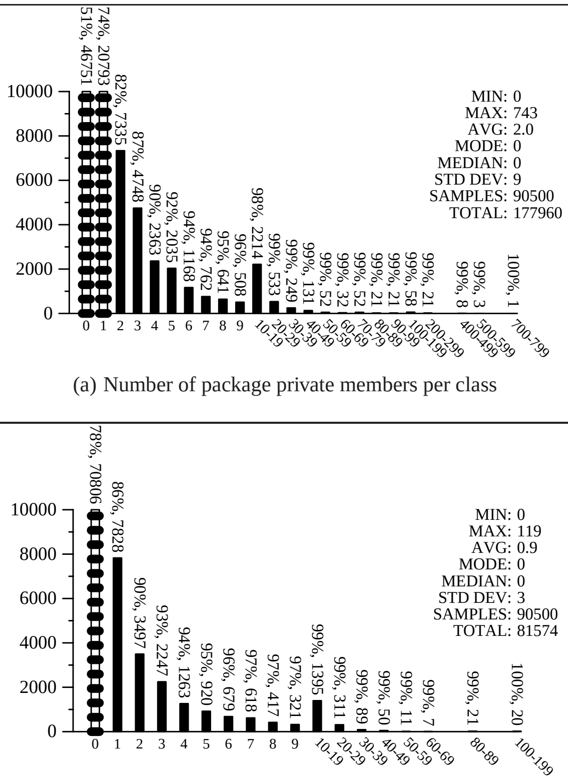
Figure 15: Method declarations in classes



(a) Number of non-static methods per class

(b) Number of final methods per class

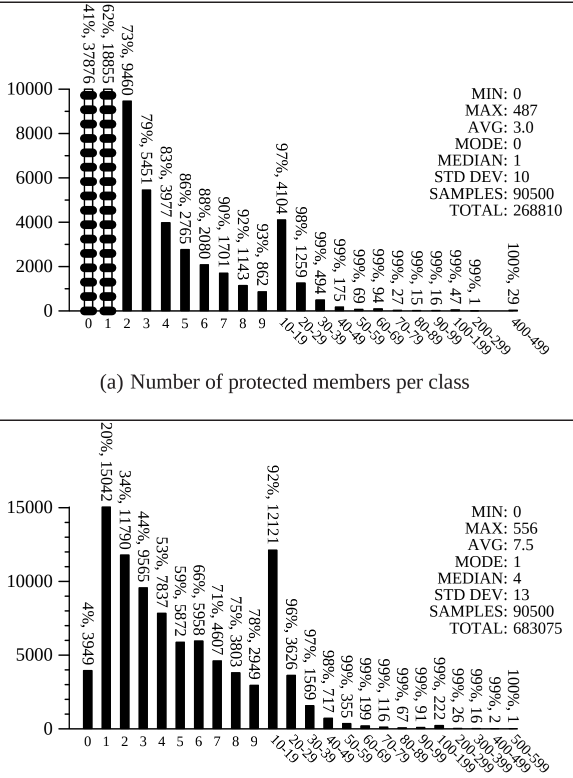
Figure 16: Method declarations in classes



(a) Number of package private members per class

(b) Number of private members per class

Figure 17: Protection of class members



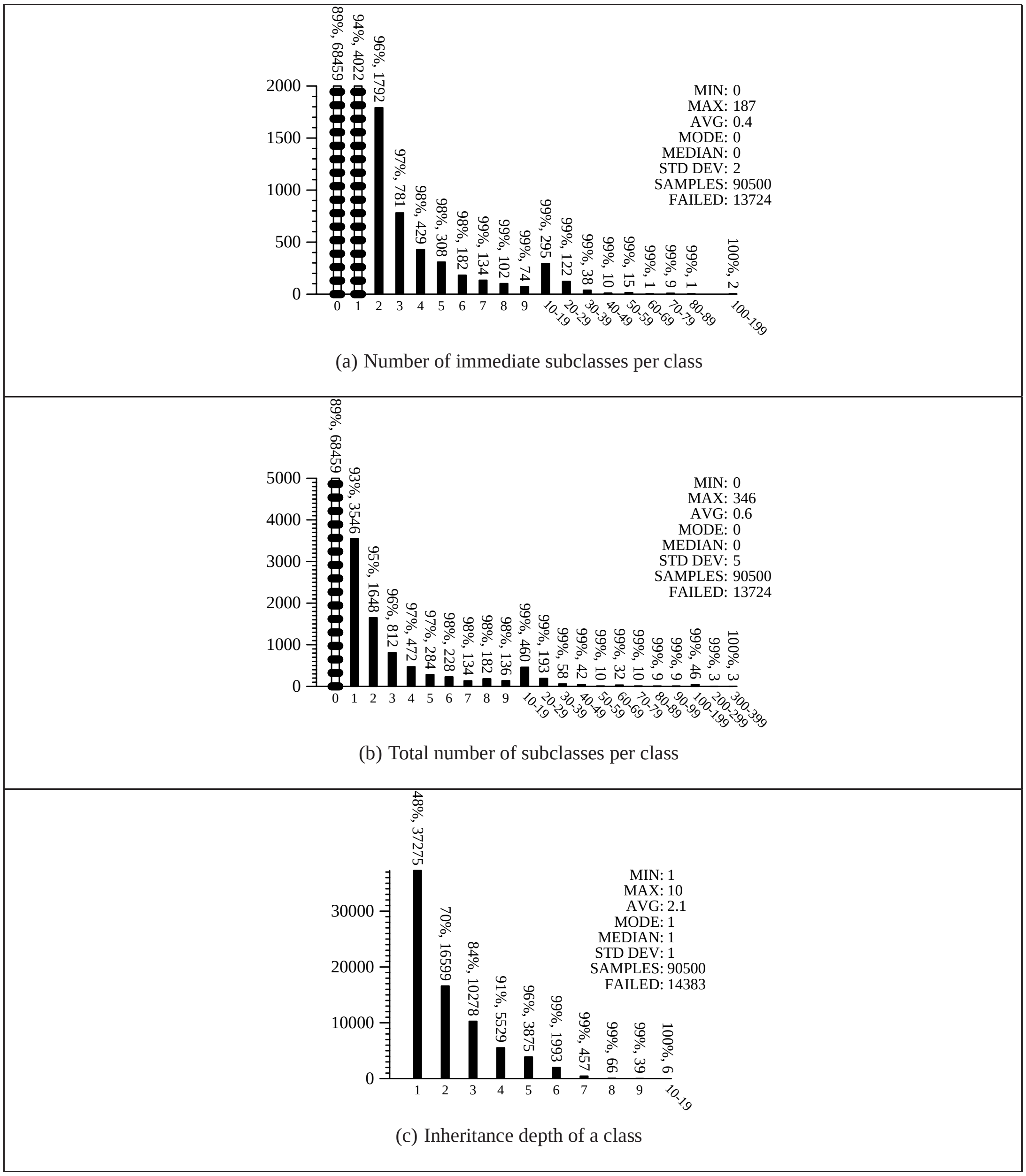
(a) Number of protected members per class

(b) Number of public methods per class

protection	**%**
package private	14.7
private	6.7
protected	22.2
public	56.4

(c) Average of class members with particular protection

Figure 18: Protection of class members

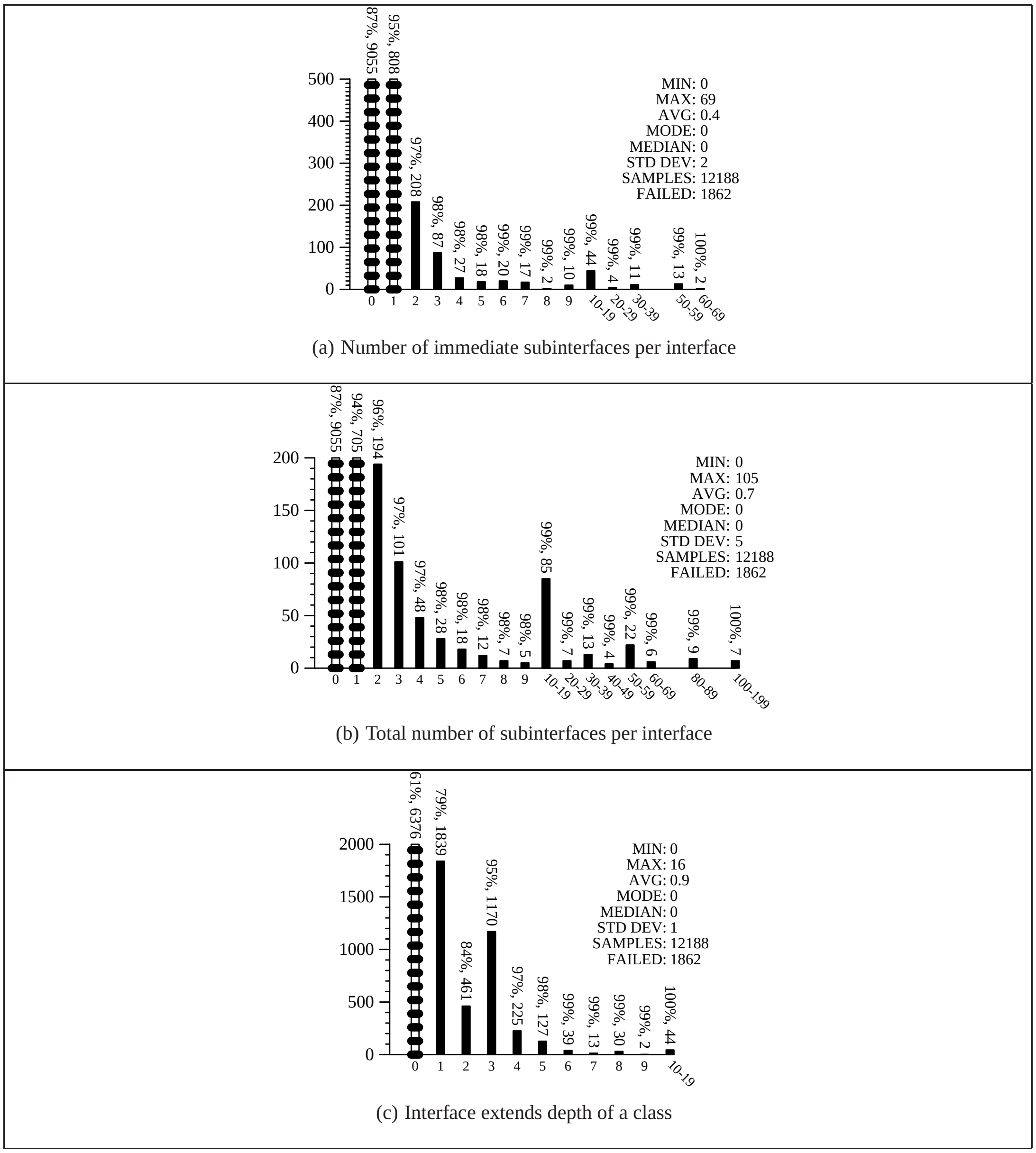


(a) Number of immediate subclasses per class

(b) Total number of subclasses per class

(c) Inheritance depth of a class

Figure 19: Sub- and superclasses



(a) Number of immediate subinterfaces per interface

(b) Total number of subinterfaces per interface

(c) Interface extends depth of a class

Figure 20: Sub- and superinterfaces

Table 8: Most common standard classes to be extended by application classes.

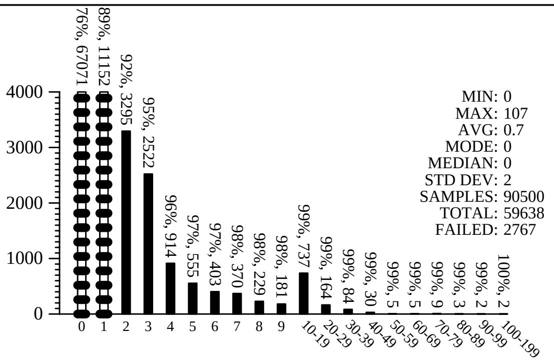
Class	Count	%
java.lang.Object	42629	47.1
user_class	34805	38.5
java.lang.Exception	1089	1.2
javax.swing.AbstractAction	893	1.0
java.lang.Thread	738	0.8
javax.swing.JPanel	691	0.8
java.lang.RuntimeException	464	0.5
java.awt.event.WindowAdapter	341	0.4
java.awt.Panel	313	0.3
java.awt.event.MouseAdapter	309	0.3
java.util.ListResourceBundle	276	0.3
java.util.EventObject	248	0.3
java.io.FilterInputStream	232	0.3
org.omg.CORBA.portable.ObjectImpl	226	0.2
org.omg.CORBA.SystemException	217	0.2
org.xml.sax.helpers.DefaultHandler	203	0.2
java.awt.Dialog	203	0.2
java.io.FilterOutputStream	202	0.2
java.applet.Applet	202	0.2
java.awt.Canvas	197	0.2
java.io.OutputStream	196	0.2
java.awt.Frame	194	0.2
java.io.IOException	192	0.2
java.io.InputStream	183	0.2
javax.swing.JFrame	149	0.2
javax.swing.JDialog	135	0.1
org.omg.CORBA.UserException	126	0.1
java.lang.Error	120	0.1
java.beans.SimpleBeanInfo	119	0.1
java.awt.event.KeyAdapter	118	0.1
javax.swing.table.AbstractTableModel	104	0.1
java.awt.event.FocusAdapter	101	0.1
java.util.AbstractSet	94	0.1
java.security.Signature	80	0.1
javax.swing.beaninfo.SwingBeanInfo	79	0.1
java.security.GeneralSecurityException	78	0.1
org.xml.sax.SAXException	70	0.1
javax.swing.JComponent	70	0.1
javax.swing.event.InternalFrameAdapter	60	0.1
java.util.Hashtable	57	0.1
java.lang.IllegalArgumentException	56	0.1
java.io.Writer	54	0.1
java.util.AbstractList	51	0.1
java.util.Properties	50	0.1
java.io.Reader	49	0.1

Table 9: Most common standard.interfaces to be implemented by application classes.

Interface	Count	%
user_interface	21955	55.9
java.io.Serializable	3534	9.0
java.awt.event.ActionListener	2880	7.3
java.lang.Runnable	1447	3.7
java.lang.Cloneable	1009	2.6
org.omg.CORBA.portable.Streamable	793	2.0
java.awt.event.ItemListener	302	0.8
java.lang.Comparable	266	0.7
java.util.Iterator	262	0.7
java.util.Enumeration	216	0.6
java.util.Comparator	215	0.5
javax.swing.event.ChangeListener	211	0.5
java.awt.event.MouseListener	187	0.5
org.xml.sax.EntityResolver	173	0.4
java.security.PrivilegedAction	145	0.4
org.xml.sax.ErrorHandler	130	0.3
java.security.spec.AlgorithmParameterSpec	130	0.3
java.beans.PropertyChangeListener	114	0.3
java.awt.event.MouseMotionListener	113	0.3
org.xml.sax.ext.LexicalHandler	109	0.3
java.awt.event.KeyListener	109	0.3
org.xml.sax.ContentHandler	100	0.3
javax.swing.event.ListSelectionListener	99	0.3
java.io.Externalizable	99	0.3
java.security.spec.KeySpec	87	0.2
org.xml.sax.DocumentHandler	83	0.2
org.xml.sax.DTDHandler	82	0.2
java.awt.event.AdjustmentListener	81	0.2
javax.sql.DataSource	80	0.2
java.awt.event.WindowListener	80	0.2
java.awt.image.ImageObserver	76	0.2
java.awt.image.renderable.RenderedImageFactory	74	0.2
javax.naming.spi.ObjectFactory	72	0.2
java.sql.Connection	71	0.2
java.awt.event.FocusListener	71	0.2
org.w3c.dom.NodeList	70	0.2
org.xml.sax.AttributeList	59	0.2
javax.naming.Referenceable	58	0.1
java.io.FilenameFilter	55	0.1
org.xml.sax.Locator	52	0.1
java.util.Map$Entry	52	0.1
java.lang.reflect.InvocationHandler	52	0.1
javax.swing.event.DocumentListener	51	0.1
java.awt.event.ComponentListener	50	0.1
org.xml.sax.Attributes	48	0.1

Table 10: Most common standard interfaces to be extended by application interfaces.

Interface	**Count**	**%**
user_interface	3359	57.7
`org.w3c.dom.html.HTMLElement`	676	11.6
`java.util.EventListener`	362	6.2
`java.io.Serializable`	251	4.3
`org.w3c.dom.Node`	225	3.9
`java.lang.Cloneable`	118	2.0
`org.omg.CORBA.Object`	96	1.6
`java.security.PrivateKey`	43	0.7
`org.w3c.dom.CharacterData`	42	0.7
`org.w3c.dom.events.EventTarget`	39	0.7
`java.security.PublicKey`	39	0.7
`org.omg.CORBA.portable.IDLEntity`	38	0.7
`org.omg.CORBA.IDLType`	36	0.6
`org.w3c.dom.Element`	29	0.5
`org.w3c.dom.Document`	28	0.5
`java.rmi.Remote`	24	0.4
`org.w3c.dom.css.CSSRule`	23	0.4
`java.security.Key`	23	0.4
`org.w3c.dom.events.Event`	22	0.4
`org.w3c.dom.DOMImplementation`	22	0.4
`org.w3c.dom.Text`	21	0.4
`org.xml.sax.XMLReader`	20	0.3
`org.omg.CORBA.IRObject`	18	0.3
`org.xml.sax.ContentHandler`	16	0.3
`java.lang.Comparable`	16	0.3
`javax.crypto.interfaces.DHKey`	14	0.2
`java.util.Map`	12	0.2
`java.sql.ResultSet`	11	0.2
`java.util.List`	10	0.2
`java.sql.Connection`	9	0.2
`java.lang.Runnable`	9	0.2
`org.w3c.dom.css.CSSValue`	8	0.1
`org.xml.sax.Locator`	7	0.1
`org.xml.sax.DTDHandler`	7	0.1
`java.util.Collection`	7	0.1
`java.sql.ResultSetMetaData`	7	0.1
`org.xml.sax.ext.LexicalHandler`	6	0.1
`org.omg.CORBA.DynAny`	6	0.1
`org.xml.sax.DocumentHandler`	5	0.1
`org.omg.CORBA.Policy`	5	0.1
`javax.xml.transform.SourceLocator`	5	0.1
`java.sql.PreparedStatement`	5	0.1
`org.w3c.dom.events.UIEvent`	4	0.1
`org.w3c.dom.events.DocumentEvent`	4	0.1



(a) Number of method overrides per class

Figure 21: Method overriding

Table 8 was computed by looking at which classes each application class extended. Every interface is considered to extend `java.lang.Object`. Similarly, Table 10 looks at which interfaces were extended by other interfaces. There is a bit of ambiguity here, because in Java source code an interface uses the *extends* keyword to extend another interface, although technically the interface is really being *implemented*. Table 9 shows which interfaces were implemented by *any* application class, including other interfaces.

Method overriding occurs when a method in a class has the same name and signature as a method in its superclass. This is a technique used to provide a more specialized implementation of a particular method. Figure 21(a) shows that the majority of classes have at most one overridden method.

6 Method-Level Statistics

In this section we present method-level statistics. This includes information about method signatures, local variables, control-flow graphs, and exception handlers.

6.1 Method sizes

Figure 22 shows the sizes in bytes and instructions of bytecode methods. The maximum size allowed by the JVM is 65535 bytes, but only one of our methods (63019 bytes long) approached this limit.

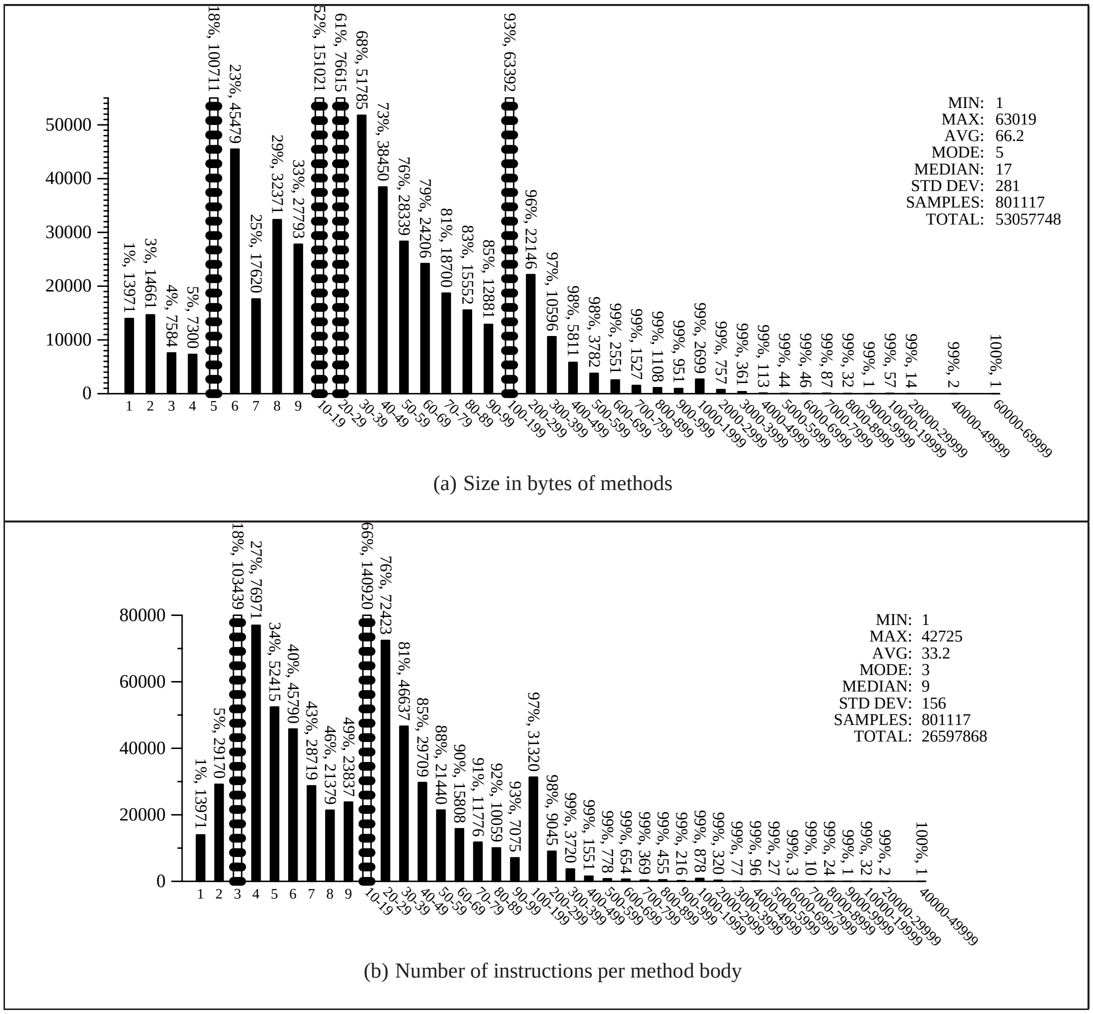
6.2 Local variables and formal parameters

Figure 23(a) shows the maximum number of slots used by a method. All instance methods will use at least one slot (for the `this` parameter). No method used more than 157 slots, indicating that the `wide` instruction (used to access up to 65536 slots) will be rarely used.

Table 11 gives a breakdown of slot types. Note that Java's `short`, `byte`, `char`, and `boolean` types are compiled into integers in the bytecode, and thus will not show up as distinct types. Also, a slot may contain more than one type within a method, although at any one particular location it must always have the same type. Table 11 shows that `int`s and `String`s make up the majority of slot types. Only 3.8% of slots contain two types, and only 0.6% 3 types. This indicates that the design of the Java virtual machine could have been simplified by requiring each slot to contain exactly one type throughout the body of a method, without much adverse effect.

Slots are not explicitly typed in the bytecode. Instead, slot types have to be computed using a static analysis known as *stack simulation*. This involves simulating the behavior of each instruction on the stack and the local variable slots, while following all possible paths of control flow within the method. A similar algorithm is used in the Java bytecode verifier.

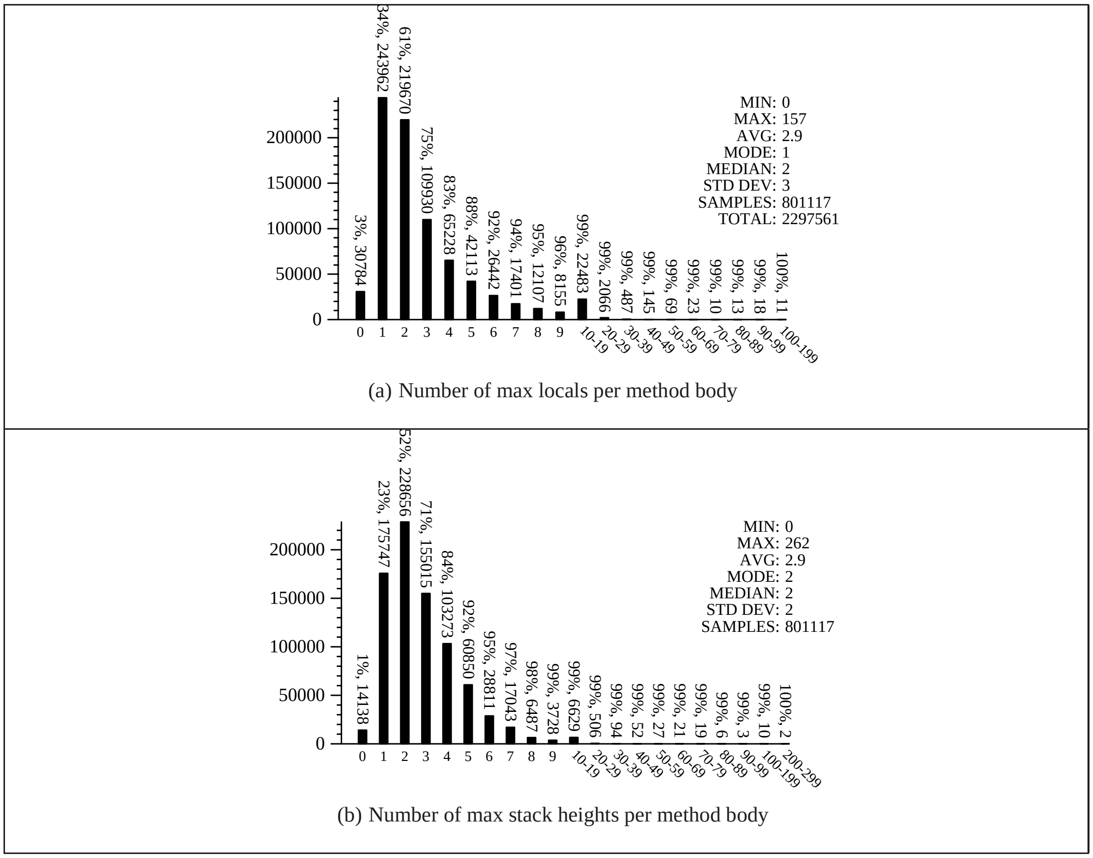
Figure 23(b) shows the maximum stack depth required by a method. This is stored as an attribute in the class file, and could thus be larger then the *actual* stack size needed at runtime.



(a) Size in bytes of methods

(b) Number of instructions per method body

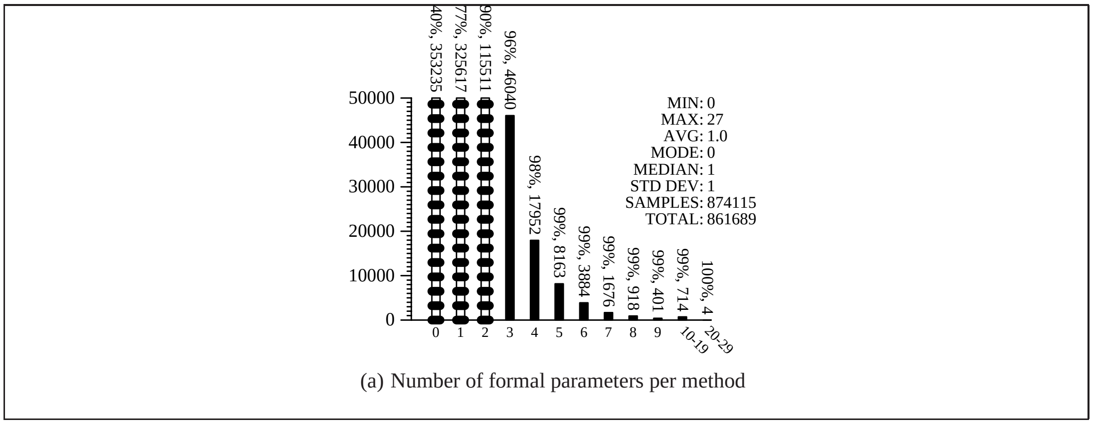
Figure 22: Method sizes



(a) Number of max locals per method body

(b) Number of max stack heights per method body

Figure 23: Local variables



(a) Number of formal parameters per method

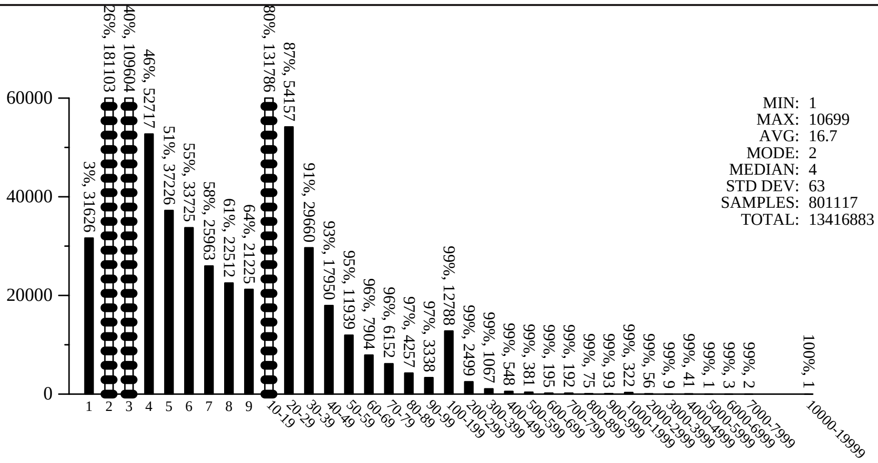
Figure 24: Formal parameters

Table 11: Most common slot types.

Register Type	**Count**	**%**
`int`	614910	16.2
`java.lang.String`	365915	9.6
2 types	144145	3.8
`java.lang.Object`	76764	2.0
`byte[]`	50658	1.3
`long`	49903	1.3
`java.lang.Throwable`	38046	1.0
`double`	25541	0.6
3 types	23426	0.6
`java.lang.StringBuffer`	21716	0.6
`java.lang.String[]`	20600	0.5
`java.util.Iterator`	16036	0.4
`float`	15595	0.4
`java.lang.Class`	15129	0.4
`java.util.Vector`	14795	0.4
`int[]`	14604	0.4
`java.lang.Exception`	14149	0.4
`java.io.File`	13334	0.4
`java.io.InputStream`	11686	0.3
`java.util.List`	11615	0.3
`java.lang.ClassNotFoundException`	11331	0.3
`java.util.Enumeration`	10732	0.3
`char[]`	9534	0.3
`java.lang.Object[]`	9417	0.2

Table 12: Most common method signatures.

Method Signature	Count	%
()void	120997	13.8
(*user_class*)void	57762	6.6
()java.lang.String	53047	6.1
()*user_class*	44098	5.0
(java.lang.String)void	43810	5.0
()boolean	39772	4.5
()int	35064	4.0
(int)void	18959	2.2
(boolean)void	11461	1.3
(*user_class*)*user_class*	10332	1.2
(*user_class*,*user_class*)void	9652	1.1
(java.lang.String)*user_class*	7781	0.9
(java.lang.String)java.lang.String	7777	0.9
(*user_class*)boolean	6880	0.8
(*user_class*)java.lang.Object	6812	0.8
()java.lang.Object	6461	0.7
(java.lang.String)java.lang.Class	6258	0.7
(java.lang.String,java.lang.String)void	5561	0.6
(java.lang.Object)boolean	5373	0.6
(int)int	4776	0.5
(java.lang.Object)void	4697	0.5
(java.awt.event.ActionEvent)void	4479	0.5
(int)*user_class*	4270	0.5
(int)boolean	4116	0.5
(java.lang.String[])void	4044	0.5
(java.lang.String)boolean	3933	0.4
(int,int)void	3726	0.4
(int)java.lang.String	3473	0.4
()byte[]	3380	0.4
()*user_class*[]	3322	0.4
(*user_class*,int)void	3251	0.4
()java.util.List	2970	0.3
(*user_class*,java.lang.String)void	2821	0.3
(byte[])void	2697	0.3
()java.lang.String[]	2292	0.3
(*user_class*,*user_class*)*user_class*	2289	0.3
(int,int)int	2023	0.2
(java.awt.event.MouseEvent)void	2008	0.2
(*user_class*)int	1998	0.2
(java.lang.String)int	1993	0.2
(*user_class*)java.lang.String	1951	0.2
()org.omg.CORBA.TypeCode	1941	0.2
(java.lang.String,*user_class*)void	1900	0.2
(java.lang.Object)*user_class*	1873	0.2



(a) Number of basic blocks (in CFGs with implicit exception edges) per method body

Figure 25: Control-Flow Graphs

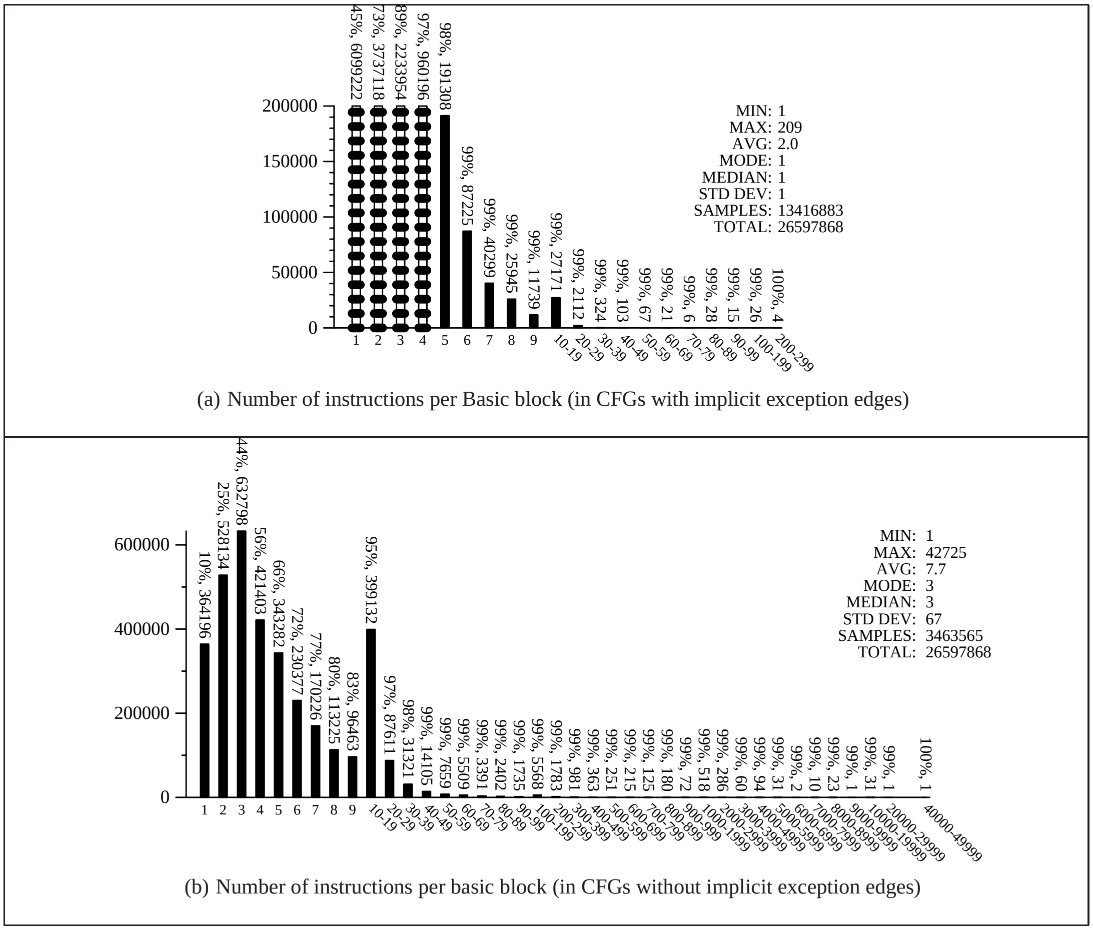
The number of slots used by a method in Figure 23(a) includes those slots reserved for method parameters. Figure 24(a) breaks out the number of formal parameters per method. This is the number of parameters, not the number of slots those parameters would consume (i.e. longs and doubles count as 1). As expected, the average is low (1.0), with 90% of all methods having 2 or fewer formals. Table 12 shows the most common method signatures. One reason that "`()void`" is so common is that this is the signature of default constructors, especially the one for `java.lang.Object`, which must be called in the constructors of all classes that directly extend it.

6.3 Control-flow graphs

A a method body can be converted into a control-flow graph (CFG), where the nodes (the *basic blocks*) are straight-line pieces of code. Control always enters the top of the basic block and exits at the bottom, either through an explicit branch or by *falling-through* to another block. There is an edge from basic block *A* to basic block *B* if control can flow from *A* to *B*.

Building CFGs for Java bytecode is not straight-forward. A major complication is how to deal with exception handling. Several instructions in the JVM can throw exceptions implicitly. This includes the division instructions (which may throw a divide-by-zero exception), and the `getfield`, `putfield`, and `invokevirtual` instructions (which may throw `null`-reference exceptions). These changes in control flow can be represented by adding *exception edges* to the CFG, which connect a basic block ending in an exception-throwing instruction to the CFG's sink node. If every such instruction (which are very common in real code) is allowed to terminate a basic block, blocks become very small. Since some analyses can safely ignore implicit exceptions, SandMark supports building the CFGs both with and without implicit exception edges. The `jsr` and `ret` instructions used for Java's `finally`-clause also cause problems. In general, a data flow analysis is necessary in order to correctly build CFGs in the presence of complex `jsr`/`ret` combinations. SandMark currently does not support this and, as a consequence, will sometimes introduce spurious edges out of blocks ending in `ret` instructions. Since there are few such CFGs in our sample set this problem is unlikely to significantly affect our data.

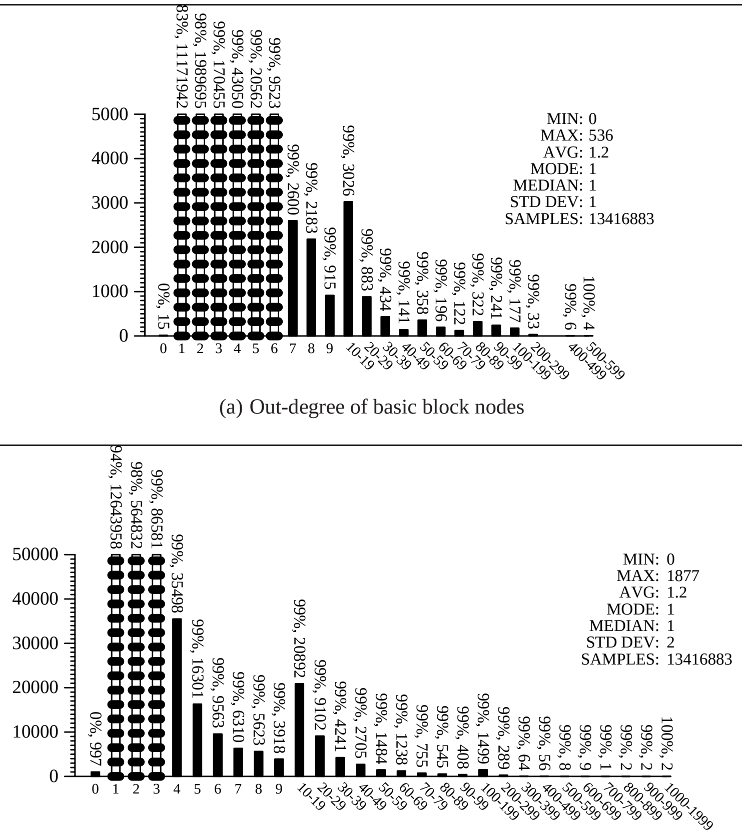
As can be seen from Figure 26(a), the average number of instructions in a basic block is very small, only 2.0, and 98% of all blocks have fewer than 6 instructions. The average out-degree of a basic block node is, predictably, low, only 1.2. Higher out-degrees than two can only be achieved either when an instruction is inside an exception handler's `try` block, or with the JVM's `tableswitch` and `lookupswitch` instructions. In the first case, edges are added from each basic block inside a `try` block to the first basic block of the handler code. Therefore, if a basic block is inside multiple nested `try` blocks its outdegree may be high. In the second case, the `tableswitch` and `lookupswitch` instructions are Java's implementation of `switch`-statements, which may have many possible branch targets.



(a) Number of instructions per Basic block (in CFGs with implicit exception edges)

(b) Number of instructions per basic block (in CFGs without implicit exception edges)

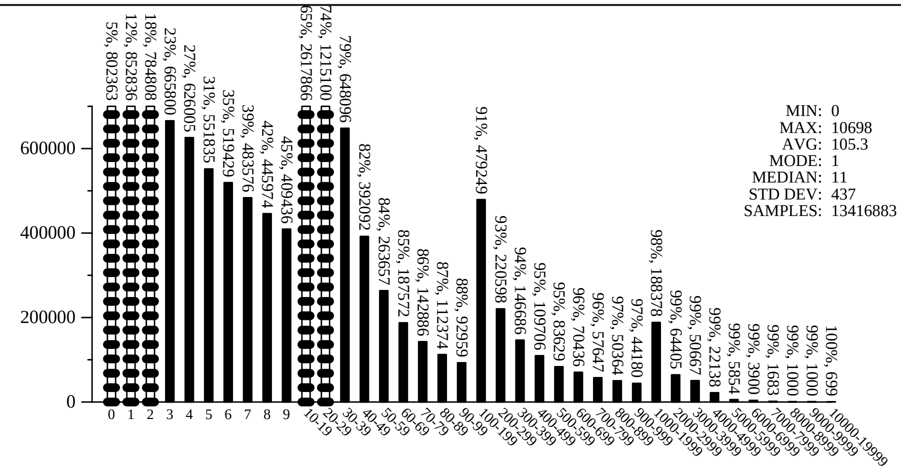
Figure 26: Control-Flow Graphs



(a) Out-degree of basic block nodes

(b) In-degree of basic block nodes

Figure 27: Control-Flow Graphs



(a) Number of dominator blocks per Basic block (in CFGs with implicit exception edges)

Figure 28: Control-Flow Graphs

Figure 26(b) shows the number of instructions per basic block when implicit exception edges have not been generated. As can be seen, this increases the average number of instructions per block to 7.7.

A node *x* in a directed graph *G* with a single exit node dominates node *y* in *G* if every path from the entry node to *y* must pass through *x*. The dominator set of a node *y* is the set of all nodes which dominate *y*. Dominator information is used in code optimizations such as loop identification and code motion. Table 28 shows the number of dominator blocks per basic block.

6.4 Subroutines and exception handlers

Java subroutines are implemented by the instructions `jsr` and `ret`. They are chiefly used to implement the finally clause of an exception handler. This clause can be reached from multiple locations. For example, a `return` instruction within the body of a `try`-block will first jump to the finally clause before returning from the method. Similarly, before returning from within an exception handler, the finally block must be executed. To avoid code duplication (inlining the finally block at every location from which it could be called) the designers of the JVM added the `jsr` and `ret` instructions to jump to and return from a block of code. This has caused much complication in the design of the JVM verifier. See, for example, Stata et al. [21]. Figure 29 shows that 98% of methods have no more than two exception handlers, and 98% of all methods have no subroutines. Figure 29(c) shows that the average size of a subroutine is 7.5 instructions. The length of a subroutine was computed as the number of instructions between a `jsr`'s target and its corresponding `ret`. Together, our data indicates that `jsr` and `ret` could have been left out of the JVMs instruction set without out much code increase from `finally`-clauses being implemented by code duplication.

6.5 Interference graphs

An interference graph models the variables and live range interferences of a method. The live ranges of a variable are the locations in a method between where the variable is first assigned to and where it is last used. The graph has one vertex per local variable and an edge between two vertices when the corresponding variables' live ranges interfere. As an example consider the sample code in Figure 31(a) and the corresponding interference graph in Figure 31(b). Since the code has 5 variables, the graph has 5 nodes. The graph has an edge $v_1 \rightarrow v_2$ since variables v_1 and v_2 are live at the same time. An interference graph is often used during the code generation pass of a compiler to perform register allocation. Two variables with intersecting live ranges cannot be assigned to the same register. Figure 30 shows that 95% of the methods have 9 or fewer nodes.

7 Instruction-Level Statistics

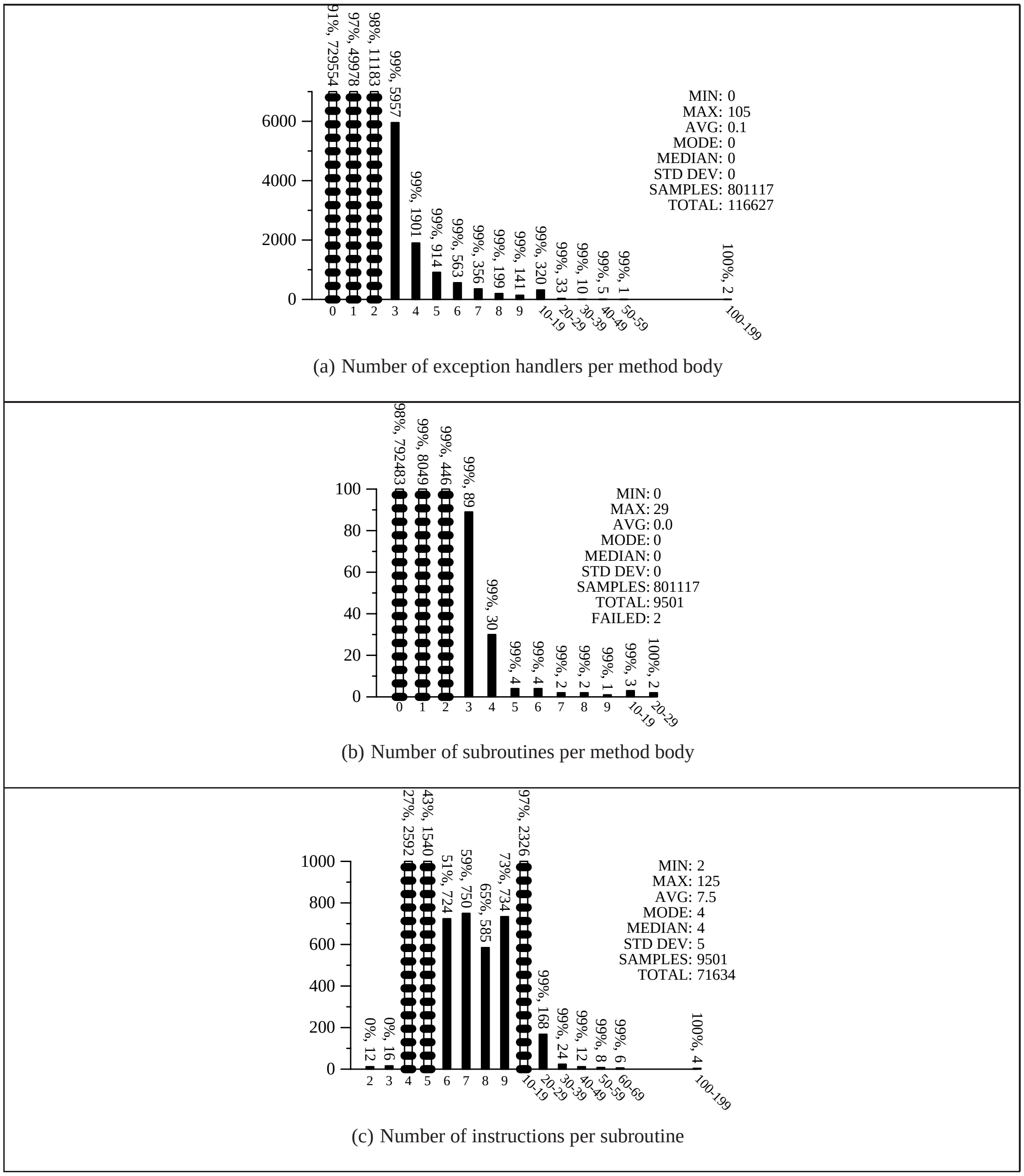
In this section we present information regarding the frequency of individual instructions and patterns of instructions. We also show the most common sub-expressions and constant values found in the bytecode.

7.1 Instruction counts

There are 200 usable Java virtual machine instruction opcodes. Tables 13 and 14 show the frequency of each of those bytecode instructions. The most frequently occuring instruction is `aload_0` which is responsible for pushing the local variable 0, the `this` reference of non-static methods. Even though this is the most frequently occuring instruction it only has a frequency of 10%. The `invokevirtual` instruction which calls a non-static method is also common, as is `getfield`, `dup`, and `invokespecial`, the last two being used to implement Java's `new` operator. These 5 instructions account for 33.8% of all instructions. Our data indicates that the majority of the remaining instructions each occur with a frequency of at most 1%, and that the `jsr_w` and `goto_w` instructions (used for long branches) do not occur at all.

7.2 Instruction patterns

A *k*-gram is a contiguous substring of length *k* which can be comprised of letters, words, or in our case opcodes. The *k*-gram is based on static analysis of the executable program. To compute the unique set of *k*-grams for a method we slide a window of length *k* over the static instruction sequence as it is laid out in the class file.

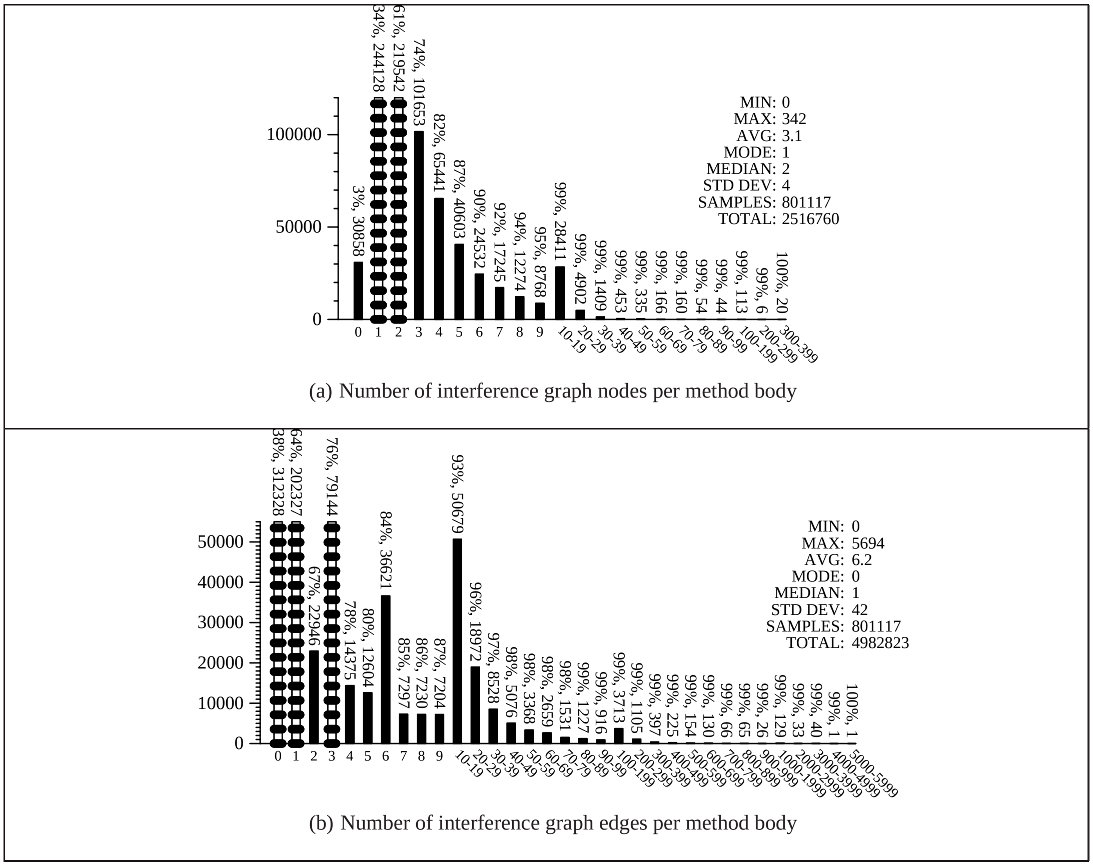


(a) Number of exception handlers per method body

(b) Number of subroutines per method body

(c) Number of instructions per subroutine

Figure 29: Exception handlers



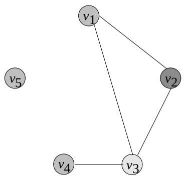
(a) Number of interference graph nodes per method body

(b) Number of interference graph edges per method body

Figure 30: Interference graphs

$$v_1 = a \times a$$
$$v_2 = a \times b$$
$$v_3 = 2 \times v_2$$
$$v_4 = v_1 + v_2$$
$$v_5 = b \times v_3$$

(a) Sample code.



(b) Interference graph.

Figure 31: Sample code and corresponding interference graph.

Table 13: Instruction frequences (A).

Op	Count	%
aload_0	2672134	10.0
invokevirtual	2360924	8.9
dup	1521855	5.7
getfield	1447792	5.4
invokespecial	1003439	3.8
ldc	936890	3.5
aload_1	909356	3.4
aload	876138	3.3
bipush	865346	3.3
new	665727	2.5
iconst_0	634481	2.4
iload	601808	2.3
putfield	552241	2.1
goto	507322	1.9
iconst_1	495114	1.9
aload_2	494004	1.9
invokestatic	457014	1.7
getstatic	438851	1.6
return	433081	1.6
astore	395436	1.5
sipush	383115	1.4
areturn	351978	1.3
aastore	332112	1.2
aload_3	314398	1.2
invokeinterface	300563	1.1
ifeq	286898	1.1
iastore	285979	1.1
ldc_w	281190	1.1
pop	270894	1.0
istore	264341	1.0
ireturn	259627	1.0
iload_2	200600	0.8
iload_1	197241	0.7
checkcast	193243	0.7
aconst_null	178499	0.7
iload_3	172820	0.6
bastore	171902	0.6
iadd	171637	0.6
ifne	167878	0.6
iconst_2	163348	0.6
athrow	151515	0.6
astore_2	144741	0.5
iinc	132890	0.5
astore_3	121477	0.5
ifnull	121318	0.5
ifnonnull	110290	0.4
aaload	108016	0.4
anewarray	106780	0.4
putstatic	105900	0.4
astore_1	99436	0.4
isub	93852	0.4
if_icmplt	89901	0.3
if_icmpne	89452	0.3
iconst_3	85851	0.3
arraylength	81083	0.3
iaload	70687	0.3
iconst_m1	67600	0.3
ldc2_w	66717	0.3
iconst_4	64544	0.2
istore_3	58529	0.2
istore_2	57750	0.2
iand	55782	0.2
instanceof	50049	0.2
if_acmpne	48379	0.2
if_icmpeq	47866	0.2
newarray	44390	0.2
iconst_5	39857	0.1
baload	39482	0.1
castore	38065	0.1
istore_1	37068	0.1
if_icmpge	35921	0.1
sastore	30690	0.1
ixor	29811	0.1
if_icmple	28212	0.1
imul	27174	0.1
iload_0	26837	0.1
dload	26640	0.1
lastore	23738	0.1
ifle	23025	0.1
monitorexit	22023	0.1
jsr	20074	0.1
lconst_0	19617	0.1
nop	18136	0.1
lload	17515	0.1
ifge	17494	0.1
i2b	17432	0.1
ishl	17233	0.1
fload	16966	0.1
ior	15500	0.1
ishr	15363	0.1

Table 14: Instruction frequences (B).

Op	Count	%
lcmp	15033	0.1
dstore	14261	0.1
dup_x1	14202	0.1
dmul	14077	0.1
idiv	13833	0.1
if_icmpgt	12477	0.0
iflt	11944	0.0
caload	11871	0.0
if_acmpeq	11595	0.0
dastore	11325	0.0
astore_0	10400	0.0
tableswitch	10197	0.0
land	10047	0.0
monitorenter	9961	0.0
daload	9782	0.0
fastore	9708	0.0
ret	9670	0.0
dconst_0	9295	0.0
i2l	8832	0.0
fstore	8765	0.0
lookupswitch	8738	0.0
lload_1	8723	0.0
faload	8634	0.0
iushr	8468	0.0
dadd	8407	0.0
i2d	8403	0.0
ifgt	7976	0.0
fmul	7674	0.0
lstore	7512	0.0
dup2	7332	0.0
lload_2	7125	0.0
ddiv	6644	0.0
lload_3	6514	0.0
dsub	5882	0.0
i2c	5839	0.0
l2i	5680	0.0
dload_1	5548	0.0
fadd	5515	0.0
irem	5508	0.0
dreturn	5159	0.0
dconst_1	5146	0.0
dcmpl	5065	0.0
i2f	5003	0.0
lreturn	4935	0.0
ladd	4621	0.0
fsub	4463	0.0
i2s	4338	0.0
d2i	4331	0.0
fconst_0	4316	0.0
f2d	4086	0.0
laload	3781	0.0
dload_3	3538	0.0
lconst_1	3515	0.0
dload_2	3286	0.0
fload_1	3261	0.0
lsub	3212	0.0
fload_2	3130	0.0
dcmpg	3040	0.0
dup_x2	2984	0.0
fdiv	2930	0.0
saload	2867	0.0
ineg	2577	0.0
multianewarray	2500	0.0
d2f	2402	0.0
freturn	2360	0.0
fload_3	2357	0.0
lshl	2195	0.0
fconst_1	2122	0.0
dload_0	2093	0.0
lload_0	1982	0.0
fcmpl	1917	0.0
istore_0	1787	0.0
lstore_3	1727	0.0
lmul	1664	0.0
lor	1520	0.0
lstore_2	1475	0.0
f2i	1391	0.0
lshr	1386	0.0
lstore_1	1352	0.0
fcmpg	1243	0.0
dneg	1230	0.0
dstore_3	1215	0.0
ldiv	1194	0.0
lxor	1146	0.0
dstore_2	1085	0.0
lushr	993	0.0
dstore_1	908	0.0
l2d	878	0.0
swap	849	0.0
fconst_2	839	0.0
fstore_3	695	0.0
fstore_2	650	0.0
lrem	539	0.0
fload_0	510	0.0
fneg	496	0.0
pop2	378	0.0
fstore_1	374	0.0
d2l	273	0.0
dup2_x1	263	0.0
lneg	208	0.0
l2f	187	0.0
dstore_0	168	0.0
dup2_x2	164	0.0
lstore_0	159	0.0
drem	55	0.0
f2l	42	0.0
fstore_0	20	0.0
frem	12	0.0
jsr_w	0	0.0
goto_w	0	0.0

Table 15: Most common 2-grams.

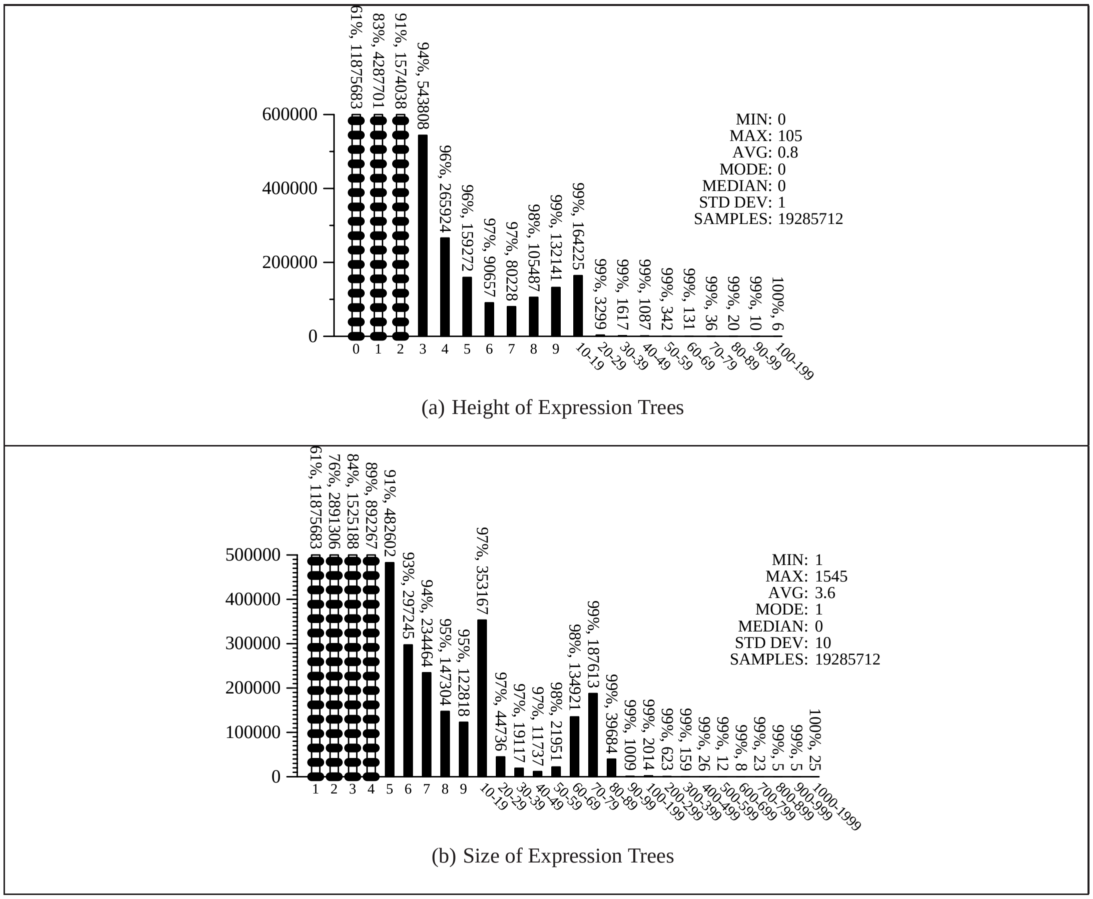
Op	Count	%
aload_0,getfield	1219837	4.7
new,dup	664718	2.6
ldc,invokevirtual	353412	1.4
invokevirtual,invokevirtual	332487	1.3
dup,bipush	330887	1.3
putfield,aload_0	311038	1.2
iastore,dup	250744	1.0
invokevirtual,aload_0	235924	0.9
dup,sipush	226520	0.9
aload_1,invokevirtual	223958	0.9
aload,invokevirtual	222692	0.9
getfield,invokevirtual	219107	0.8
aload_0,aload_1	214369	0.8
aastore,dup	208247	0.8
dup,invokespecial	202840	0.8
aload_0,invokevirtual	200872	0.8
invokevirtual,pop	193105	0.7
aload_0,invokespecial	159742	0.6
astore,aload	146309	0.6
bastore,dup	141779	0.5
ldc,aastore	133994	0.5
getfield,aload_0	129300	0.5
invokespecial,aload_0	122168	0.5
ldc,invokespecial	120935	0.5
dup,ldc	116043	0.4
invokespecial,athrow	115994	0.4
aload_2,invokevirtual	115394	0.4
goto,aload_0	115340	0.4
putfield,return	113044	0.4
dup,iconst_0	109473	0.4
invokevirtual,ldc	109060	0.4
invokevirtual,return	106765	0.4
invokevirtual,ifeq	103093	0.4
bipush,bastore	102969	0.4
invokevirtual,astore	100355	0.4
ifeq,aload_0	99667	0.4
bipush,bipush	98715	0.4
ldc_w,iastore	98376	0.4
iconst_0,ireturn	98199	0.4
invokevirtual,aload	93325	0.4
aload_0,new	90040	0.3
anewarray,dup	81992	0.3
dup,aload_0	80579	0.3
aload_0,aload_0	80329	0.3
aload,aload	78718	0.3

Table 16: Most common 3-grams.

Op	Count	%
new,dup,invokespecial	202836	0.8
aload_0,getfield,invokevirtual	194765	0.8
iastore,dup,bipush	132759	0.5
invokevirtual,aload_0,getfield	125019	0.5
new,dup,ldc	115036	0.5
aload_0,getfield,aload_0	111950	0.4
getfield,aload_0,getfield	111002	0.4
iastore,dup,sipush	102667	0.4
bipush,bastore,dup	100197	0.4
invokevirtual,ldc,invokevirtual	98964	0.4
ldc_w,iastore,dup	97826	0.4
dup,ldc,invokespecial	91303	0.4
aload_0,new,dup	90029	0.4
dup,bipush,bipush	83402	0.3
ldc,aastore,dup	82970	0.3
anewarray,dup,iconst_0	81984	0.3
aastore,dup,bipush	80740	0.3
new,dup,aload_0	80524	0.3
invokevirtual,invokevirtual,invokevirtual	80161	0.3
invokespecial,ldc,invokevirtual	69626	0.3
aload_0,getfield,aload_1	68922	0.3
bastore,dup,sipush	67634	0.3
aload_0,invokespecial,aload_0	66723	0.3
dup,sipush,bipush	64736	0.3
aload_0,aload_1,putfield	60661	0.2
bastore,dup,bipush	60580	0.2
goto,aload_0,getfield	60205	0.2
aload_0,aload_0,getfield	58350	0.2
dup,invokespecial,ldc	57764	0.2
dup,sipush,ldc_w	57139	0.2
dup,bipush,ldc_w	56309	0.2
aastore,dup,iconst_1	56004	0.2
putfield,aload_0,getfield	55324	0.2
aastore,aastore,dup	55149	0.2
aload_0,getfield,areturn	55073	0.2
ldc,invokevirtual,invokevirtual	53465	0.2
new,dup,aload_1	52185	0.2
ldc,invokevirtual,aload_0	51342	0.2
invokespecial,putfield,aload_0	50827	0.2
sipush,bipush,bastore	50642	0.2
dup,bipush,ldc	50439	0.2
dup,iconst_0,ldc	49992	0.2
aload_0,getfield,getfield	49974	0.2
iconst_0,ldc,aastore	49056	0.2
sipush,ldc_w,iastore	48252	0.2

Table 17: Most common 4-grams.

Op	Count	%
aload_0,getfield,aload_0,getfield	95199	0.4
new,dup,ldc,invokespecial	91302	0.4
new,dup,invokespecial,ldc	57764	0.2
dup,invokespecial,ldc,invokevirtual	57239	0.2
bipush,bastore,dup,sipush	50663	0.2
dup,sipush,bipush,bastore	50642	0.2
bastore,dup,sipush,bipush	50642	0.2
sipush,bipush,bastore,dup	50392	0.2
anewarray,dup,iconst_0,ldc	48862	0.2
dup,iconst_0,ldc,aastore	48697	0.2
iastore,dup,sipush,ldc_w	48252	0.2
dup,sipush,ldc_w,iastore	48252	0.2
ldc_w,iastore,dup,sipush	48198	0.2
sipush,ldc_w,iastore,dup	47875	0.2
iastore,dup,bipush,ldc_w	47528	0.2
dup,bipush,ldc_w,iastore	47528	0.2
ldc_w,iastore,dup,bipush	47520	0.2
bipush,ldc_w,iastore,dup	47384	0.2
dup,bipush,bipush,bastore	44682	0.2
bastore,dup,bipush,bipush	44680	0.2
bipush,bastore,dup,bipush	44674	0.2
bipush,bipush,bastore,dup	44209	0.2
aload_0,new,dup,invokespecial	43141	0.2
new,dup,new,dup	42678	0.2
invokevirtual,ldc,invokevirtual,invokevirtual	42594	0.2
ldc,aastore,aastore,dup	41430	0.2
aastore,aastore,dup,bipush	40443	0.2
dup,ldc,invokespecial,athrow	40441	0.2
new,dup,aload_0,getfield	36325	0.1
new,dup,invokespecial,putfield	34800	0.1
ldc,aastore,dup,iconst_1	34705	0.1
iconst_0,ldc,aastore,dup	34705	0.1
aastore,dup,iconst_1,ldc	34585	0.1
putfield,aload_0,new,dup	34499	0.1
dup,iconst_1,ldc,aastore	34191	0.1
invokevirtual,aload_0,getfield,invokevirtual	34185	0.1
aload_0,iconst_0,putfield,aload_0	33108	0.1
aload_0,aload_1,putfield,return	32147	0.1
aload_0,aconst_null,putfield,aload_0	31719	0.1
aload_0,getfield,aload_1,invokevirtual	31472	0.1
iconst_2,anewarray,dup,iconst_0	30710	0.1
ldc,invokevirtual,aload_0,getfield	30470	0.1
putfield,aload_0,iconst_0,putfield	27739	0.1
iastore,dup,bipush,ldc	26735	0.1
dup,bipush,ldc,iastore	26735	0.1



(a) Height of Expression Trees

(b) Size of Expression Trees

Figure 32: Expressions

We computed data for k-grams where $k = 2, 3, 4$ which is shown in Tables 15, 16, and 17. These tables show that as the value of k increases the percentage of the most frequency ocurring sequences decreases. For example, the most frequently occuring 2-gram, `aload_0, getfield`, has a frequency of only 4.7%. For 2 and 3-grams the most frequently occuring sequence is less than 1%. This indicates that these sequences become quite unique for each individual application.

7.3 Expressions

Figure 32 shows the size (number of nodes in the tree) and height (length of longest path from root to leaf) of expression trees in our samples. As reported already by Knuth [15], expressions tend to be small. 61% of all expressions only have one node.

Expressions are constructed by performing a stack simulation over each method. For each instruction that will produce a result on the stack the simulator determines which instructions may have put its operands on the stack. This information is used to build up a dependency graph with instructions and operands as nodes, and an edge from node a to node b if b is used by a. If the program contains certain types of loops these graphs might have cycles, in which case they are discarded. The following code segment is an example of such a loop:

```
0: ICONST_2
1: ICONST_3
2: IADD
3: DUP
4: IFEQ <1>
```

Table 18: Abbreviations used in Table 19.

null	≡	ACONST_NULL	((τ)α)	≡	typecast, τ is a primitive type or *Class*
-(α)	≡	negation			
(α+α)	≡	addition	A	≡	create new array
(α-α)	≡	subtraction	S	≡	static field
(α*α)	≡	mult	F	≡	non-static field
(α/α)	≡	div	M()	≡	method call
(α%α)	≡	mod/rem	(α instanceof κ)	≡	instanceof
(α&α)	≡	and	"	≡	string constant
(α|α)	≡	or	f	≡	float constant
(α^α)	≡	xor	d	≡	double constant
(α<<α)	≡	left shift	l	≡	long constant
(α>>α)	≡	signed right shift	N	≡	NEW
(α>>>α)	≡	IUSHR or LUSHR	(α<α)	≡	DCMPL or FCMPL
α[]	≡	array element	(α>α)	≡	DCMPG or FCMPG
α.length	≡	ARRAYLENGTH	(α<>α)	≡	LCMP
i	≡	int constant	L	≡	load local variable

In this example, the IADD instruction may become its own child. If the branch at offset 4 is taken, then the result from the first iteration of the IADD will be used as the first operand in the second iteration of the IADD.

In Table 19 we show the most common subexpressions found in our sample method bodies. Table 18 explains the abbreviations used. L, for example, represents a local variable, d a double constant, (α+α) addition, etc. Since we are counting subexpressions, the same piece of an expression will be counted more than once. For example, if x and y are local variables then the expression x+y*2 will generate subexpressions L, L, i, (L*i), and (L+(L*i)), each of which will increase the count of its respective expression class.

To compute subexpressions we convert each expression tree into a string representation, classify each subexpression into equivalence classes according to Table 18, and count each subexpression individually.

What we see from Table 19 is that, unsurprisingly, local variable references, method calls, integer constants, and field references make up the bulk of expressions. Somewhat more surprising is that the expression ((*Class*)M()) is very frequent. Most likely this is the result of references to "generic" methods (particularly Java library functions such as java.util.Vector.get()) returning java.lang.Objects which then have to be cast into a more specific type.

7.4 Constant values

Tables 20, 21, and 22 show the most common literal constants found in the bytecode. Constants can occur in three different ways: as references to entries in the constant pool (instructions ldc, ldc_w, and ldc2_w), as arguments to bytecode instructions (bipush *n*, sipush *n*, and iinc *n*,*c*), or embedded in special instructions (iconst_*n*, etc.).

Figure 33 shows the distribution of integer constant values. It is interesting to note that 63% of all literal integers are 0, powers of two, or powers of two plus/minus one. This has implications for, for example, software watermarking algorithms such as the one by Cousot and Cousot [11] which hides a watermark in unusual constants. Figure 33 tells us that in real programs most constants are small (93% are less than 1,000) or very close to powers of two, and hence hiding a mark in unusual constants is likely to be unstealthy.

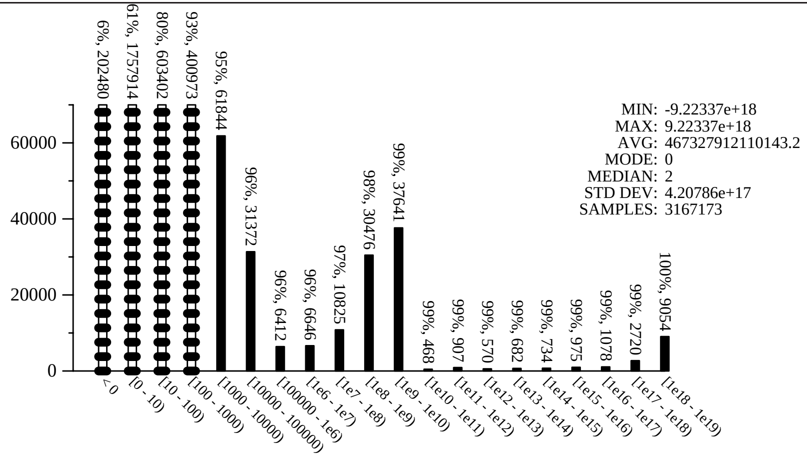
7.5 Method calls

Table 23 reports the most frequently called Java library methods. To collect this data, we looked at every INVOKE instruction to see what method it named. No attempt at method resolution was made.

Figure 34 measures the size of receiver sets of method calls. I.e., for a virtual method invocation o.M() we count the number of methods M() that might potentially be called. This depends on the static type of o, and the number of

Table 19: Most common sub-expressions.

Expression	Count	%
L	6574522	34.9
M()	4119506	21.9
i	2967193	15.7
L.F	1366327	7.3
"	1039672	5.5
N	665727	3.5
S	438851	2.3
A	153670	0.8
L[]	121966	0.6
((*Class*)M())	115363	0.6
null	95366	0.5
L.F[]	83259	0.4
l	67088	0.4
L.F.F	54078	0.3
L.length	51938	0.3
((*Class*)L)	49937	0.3
(L+i)	41182	0.2
(L instanceof *Class*)	39081	0.2
d	37202	0.2
S[]	29776	0.2
(L+L)	24534	0.1
(L.F+i)	24296	0.1
L.F.length	23898	0.1
(L-i)	19852	0.1
f	17746	0.1
((*Class*)S)	14614	0.1
(L-L)	13495	0.1
(L&i)	13436	0.1
(L.F-i)	10759	0.1
(L>>i)	9050	0.0
(L[]&i)	8285	0.0
((*Class*)L.F)	7715	0.0
M().F	7518	0.0
(L+M())	7451	0.0
(M()-i)	7181	0.0
(L>>>i)	7181	0.0
(M() instanceof *Class*)	6305	0.0
(L<<i)	6013	0.0
(L*i)	5818	0.0
L[][]	5757	0.0
(L.F-L.F)	5509	0.0
((double)L)	5300	0.0
(L*L)	5234	0.0
L.F[][]	5230	0.0
L.F.F.F	5087	0.0
(L.F+L)	4607	0.0
(L.F&i)	4572	0.0
(M()+i)	4511	0.0
(L.F+L.F)	4326	0.0
(L&l)	4149	0.0
((L+M())+L.F[])	4128	0.0
(M()+L)	3997	0.0
(L.length-i)	3994	0.0
((L>>i)&i)	3917	0.0
(i*L)	3792	0.0
((L&l)<>l)	3734	0.0
(L/i)	3689	0.0
(L.F>>i)	3654	0.0
(((L+M())+L.F[])+i)	3392	0.0
L.F[].F	3367	0.0
S[][]	3351	0.0
(L.F instanceof *Class*)	3342	0.0
((L>>>i)&i)	3162	0.0
(L+L.F)	3051	0.0
((*Class*)L[])	2995	0.0
(L.F-L)	2977	0.0
(S[]&i)	2898	0.0
(LˆL)	2818	0.0
(L.F[]&i)	2773	0.0
((long)L)	2748	0.0
((byte)L)	2699	0.0
(L.F*L.F)	2690	0.0
S.length	2626	0.0
(l&L)	2618	0.0
((l&L)<>l)	2612	0.0
((double)L.F)	2509	0.0
((L[]&i)<<i)	2473	0.0
L.F.F[]	2437	0.0
(L-L.F)	2423	0.0
-(L)	2423	0.0
(L<>l)	2322	0.0
(L&L)	2285	0.0
((L.F>>i)&i)	2275	0.0
S.F	2214	0.0
((char)L)	2201	0.0
(S+i)	2132	0.0
((float)L)	2129	0.0
((int)M())	2081	0.0



(a) Distribution of integers (`int` and `long`)

Value	Count	%
`0`	654101	20.7
`1`	695404	22.0
`2`	169760	5.4
$2^n, n > 1$	205877	6.5
$2^n - 1, n > 1$	198280	6.3
$2^n + 1, n > 1$	93544	3.0
`other`	1150207	36.3

(b) Integers (`int` and `long`) close to powers of two

Figure 33: Constant Values

Table 20: Common integer constants

Value	Count	%
0	634484	20.5
1	611382	19.7
2	165656	5.3
3	86253	2.8
-1	78187	2.5
4	65209	2.1
8	45619	1.5
5	40047	1.3
10	31762	1.0
255	31249	1.0
6	29798	1.0
7	28356	0.9
9	25497	0.8
16	24931	0.8
32	19401	0.6
12	17889	0.6
13	17228	0.6
11	15763	0.5
15	15008	0.5
14	13733	0.4
24	13607	0.4
20	10844	0.3
48	9759	0.3
17	9513	0.3
63	8963	0.3
46	8540	0.3
47	8214	0.3
18	8115	0.3
34	8029	0.3
31	7681	0.2
64	7602	0.2
40	7187	0.2
21	7044	0.2
100	6984	0.2
45	6970	0.2
23	6860	0.2
19	6855	0.2
41	6631	0.2
30	6621	0.2
58	6551	0.2
128	6547	0.2
22	6510	0.2
25	6441	0.2

(a) Most common `int` constants

Value	Count	%
0	19617	29.2
1	3515	5.2
-1	2320	3.5
1000	1114	1.7
287948901175001088	740	1.1
2	722	1.1
255	669	1.0
3	387	0.6
100	347	0.5
5	344	0.5
8388608	343	0.5
4294967295	331	0.5
10	323	0.5
7	304	0.5
71776119061217280	270	0.4
4	269	0.4
60000	217	0.3
9	199	0.3
541165879422	196	0.3
9223372036854775807	190	0.3
64	182	0.3
9007199254740992	170	0.3
8	167	0.2
-9223372036854775808	160	0.2
500	159	0.2
60	156	0.2
36028797018963968	148	0.2
2147483647	144	0.2
67108864	139	0.2
3600000	134	0.2
17179869184	132	0.2
144115188075855872	132	0.2
140737488355328	130	0.2
1024	129	0.2
10000	125	0.2
137438953504	123	0.2
43980465111040	122	0.2
1099511627776	122	0.2
562949953421312	118	0.2
17592186044416	118	0.2
33554432	117	0.2
268435456	117	0.2
16384	109	0.2

(b) Most common `long` constants

Table 21: Common real constants

Value	Count	%
0.0	4316	24.3
1.0	2122	12.0
2.0	839	4.7
0.5	573	3.2
255.0	319	1.8
-1.0	311	1.8
4.0	177	1.0
100.0	164	0.9
10.0	151	0.9
0.75	146	0.8
64.0	124	0.7
3.0	124	0.7
1000.0	114	0.6
20.0	109	0.6
90.0	79	0.4
3.1415927 (π)	73	0.4
NaN	68	0.4
57.29578 ($180/\pi$)	68	0.4
50.0	68	0.4
6.2831855 (2π)	64	0.4
6.0	64	0.4
3.4028235E38 (*MAX*)	62	0.3
1.0E-4	61	0.3
180.0	60	0.3
5.0	58	0.3
0.85	58	0.3
0.1	58	0.3
0.01	52	0.3
-10.0	51	0.3
0.0010	47	0.3
8.0	45	0.3
1.5	45	0.3
0.8	45	0.3
0.3	45	0.3
0.25	45	0.3
-Infinity	44	0.2
Infinity	44	0.2
100000.0	42	0.2
1.5707964 ($\pi/2$)	40	0.2
0.70710677 ($1/\sqrt{2}$)	40	0.2
-100.0	38	0.2
200.0	37	0.2
65536.0	36	0.2

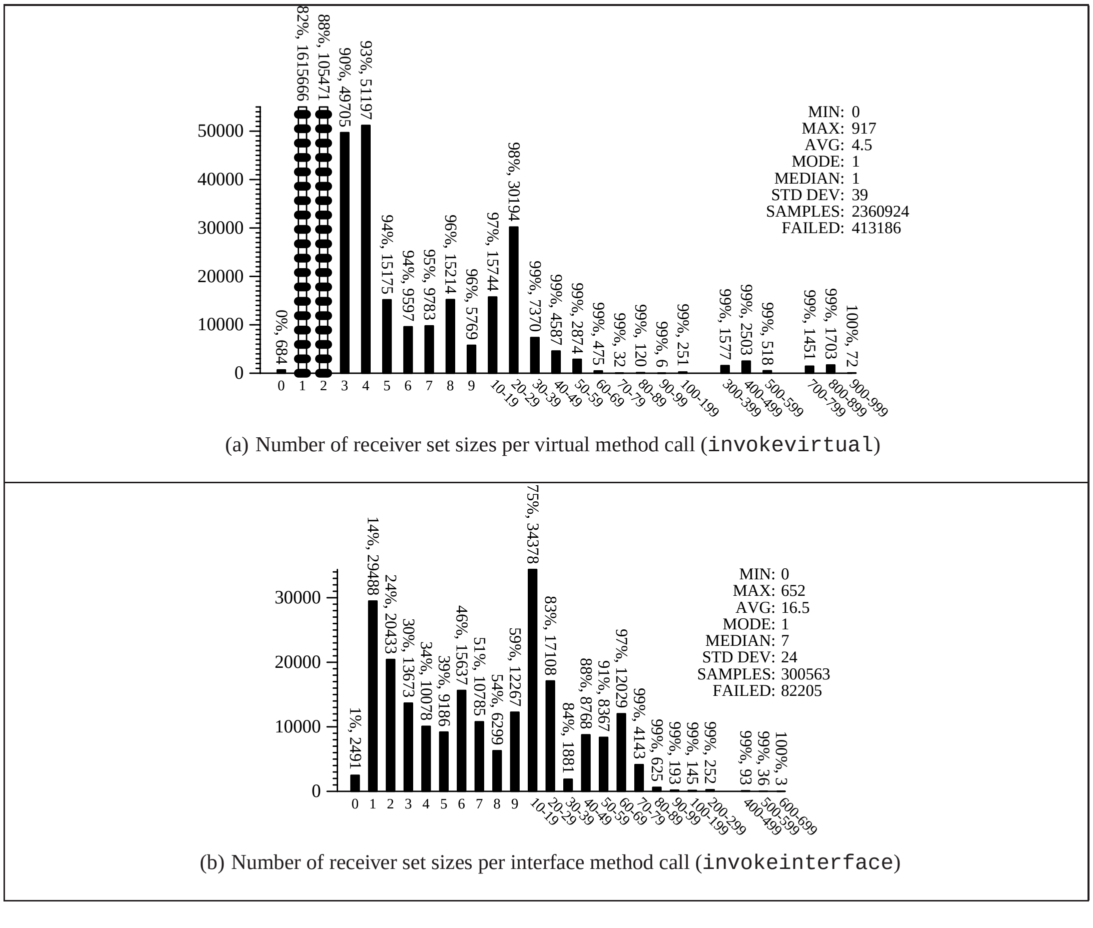
(a) Most common `float` constants

Value	Count	%
0.0	9295	25.0
1.0	5146	13.8
2.0	1920	5.2
0.5	1296	3.5
100.0	710	1.9
10.0	689	1.9
5.0	585	1.6
-Infinity	467	1.3
-1.0	463	1.2
1000.0	454	1.2
3.0	409	1.1
3.141592653589793 (π)	364	1.0
NaN	333	0.9
4.0	311	0.8
0.25	285	0.8
Infinity	206	0.6
8.0	198	0.5
1.797693$\cdots$7E308 (*MAX*)	182	0.5
180.0	162	0.4
1.5	156	0.4
0.1	152	0.4
360.0	145	0.4
20.0	120	0.3
6.283185307179586 (2π)	118	0.3
-2.0	112	0.3
0.01	107	0.3
255.0	105	0.3
0.2	104	0.3
6.0	103	0.3
0.6	92	0.2
7.0	91	0.2
9.0	88	0.2
1.25	83	0.2
16.0	77	0.2
60.0	75	0.2
31.0	72	0.2
26.0	71	0.2
0.75	71	0.2
12.0	69	0.2
0.05	67	0.2
0.3	66	0.2
15.0	65	0.2
645.0	64	0.2

(b) Most common `double` constants

Table 22: Most common string constants

Value	**Count**	**%**
empty string	36456	3.5
" "	9003	0.9
newline	5281	0.5
")"	4860	0.5
"."	4718	0.5
"S"	4540	0.4
"’"	4201	0.4
"Q"	4139	0.4
":"	4083	0.4
","	3885	0.4
"R"	3796	0.4
"P"	3663	0.4
", "	3562	0.3
"/"	3481	0.3
"""	3113	0.3
"0"	3024	0.3
"name"	2725	0.3
"("	2561	0.2
"false"	2536	0.2
"true"	2461	0.2
"]"	2115	0.2
": "	2093	0.2
"Center"	1931	0.2
"-"	1699	0.2
"BC"	1658	0.2
"PvQ"	1649	0.2
">"	1634	0.2
"id"	1450	0.1
"P->Q"	1373	0.1
"P&Q"	1370	0.1
"java.lang.String"	1314	0.1
"line.separator"	1313	0.1
";"	1307	0.1
"W"	1237	0.1
"="	1210	0.1
"shortDescription"	1207	0.1
tab	1159	0.1
"}"	1151	0.1
"RvS"	1110	0.1
"null"	1107	0.1
"*"	1084	0.1
"A"	1074	0.1
"["	1046	0.1
"class"	1012	0.1
"˜P"	996	0.1



(a) Number of receiver set sizes per virtual method call (`invokevirtual`)

(b) Number of receiver set sizes per interface method call (`invokeinterface`)

Figure 34: Method calls

Table 23: Most common calls to methods in the Java library.

Method	Count	%
`java.lang.StringBuffer.append(String)StringBuffer`	340044	15.8
`StringBuffer.toString()String`	143985	6.7
`StringBuffer.<init>()void`	93837	4.3
`Object.<init>()void`	52597	2.4
`StringBuffer.<init>(String)void`	48408	2.2
`String.equals(Object)boolean`	46645	2.2
`java.util.Hashtable.put(Object,Object)Object`	42629	2.0
`java.io.PrintStream.println(String)void`	42594	2.0
`StringBuffer.append(int)StringBuffer`	31702	1.5
`StringBuffer.append(Object)StringBuffer`	27284	1.3
`String.length()int`	25505	1.2
`String.valueOf(Object)String`	20146	0.9
`java.lang.IllegalArgumentException.<init>(String)void`	15737	0.7
`StringBuffer.append(char)StringBuffer`	15116	0.7
`String.substring(int,int)String`	14441	0.7
`java.util.Vector.size()int`	13817	0.6
`java.util.Vector.addElement(Object)void`	12705	0.6
`java.util.Vector.elementAt(int)Object`	12087	0.6
`java.lang.System.arraycopy(Object,int,Object,int,int)void`	11969	0.6
`java.util.Iterator.hasNext()boolean`	11891	0.6
`String.charAt(int)char`	11831	0.5
`java.util.Iterator.next()Object`	11800	0.5
`java.lang.Integer.<init>(int)void`	11658	0.5
`java.lang.Throwable.getMessage()String`	11216	0.5
`java.util.Vector.<init>()void`	10434	0.5
`java.util.List.add(Object)boolean`	10166	0.5
`Object.getClass()java.lang.Class`	9641	0.4
`java.util.Hashtable.get(Object)Object`	9584	0.4
`String.equalsIgnoreCase(String)boolean`	9391	0.4
`java.util.List.size()int`	9226	0.4
`java.util.Map.put(Object,Object)Object`	8830	0.4
`java.util.List.get(int)Object`	8797	0.4
`java.lang.Class.forName(String)java.lang.Class`	8641	0.4
`java.util.Map.get(Object)Object`	8313	0.4
`java.awt.Container.add(java.awt.Component)java.awt.Component`	8270	0.4
`String.substring(int)String`	7862	0.4
`java.io.PrintWriter.println(String)void`	7767	0.4
`java.util.Enumeration.nextElement()Object`	7539	0.3
`java.lang.Class.getName()String`	7288	0.3
`String.startsWith(String)boolean`	7186	0.3
`String.indexOf(String)int`	6960	0.3
`java.util.ArrayList.<init>()void`	6705	0.3
`java.lang.Integer.parseInt(String)int`	6667	0.3
`java.util.Enumeration.hasMoreElements()boolean`	6526	0.3
`java.lang.NullPointerException.<init>(String)void`	6403	0.3

methods in `type(o)`'s subclasses that override `o`'s `M()`. A static Class Hierarchy Analysis [12] is used to compute the receiver set.

The size of the receiver set has implications for, among other things, code optimization. A virtual method call that has only one member in its receiver set can be replaced with a direct call. Furthermore, if, for example, `o.M()`'s receiver set is {`Class1.M(), Class2.M()`}, then to expand `o.M()` inline the code `if o instanceof Class1 then Class1.M() else Class2.M()` has to be generated. The larger the receiver set, the more type tests will have to be inserted.

To compute receiver sets for an `INVOKEVIRTUAL` instruction, we first resolve the method reference. We then gather all the subclasses of the resolved method's parent class (including itself) and for each one look to see if it contains a non-abstract method with the same name and signature as the resolved method. If so, we check to see if the resolved method is accessible from the given subclass. If this is true, then the `INVOKEVIRTUAL` instruction could possibly execute the subclass's method, and it is added to the receiver set for the `INVOKEVIRTUAL` instruction.

For an `INVOKEINTERFACE` instruction, we perform the same test but we look instead at all implementors of the resolved method's parent interface. This set will contain all classes that directly implement the interface, as well as subclasses of those classes, and classes that implement any subinterfaces of the interface (i.e. anything that could be cast to the interface type). The `INVOKESPECIAL` and `INVOKESTATIC` instructions do not use dynamic method invocation; the method they will call can always be determined statically. Thus, they all have receiver sets of size 1.

Since we count only method bodies in the receiver sets, it is possible to have receiver sets of size 0. This can occur if an abstract class has no subclasses to implement its abstract methods, yet code is written to call its abstract methods with future subclasses in mind. Similarly, an `INVOKEINTERFACE` call may have no receivers if no classes implement the given interface.

Figure 34(a) shows that 88% of all virtual method calls have a receiver set with size at most 2, with the average size being 4.5. It is interesting to note the large number of methods with a receiver size between 20 and 29. As can be expected, the average receiver set size is significantly larger for an interface method call. Figure 34(b) shows an average set size of 16.5.

7.6 Switches

Figure 35(a) measures the number of *case* labels for each `tableswitch` and `lookupswitch` instruction. We had to treat the `tableswitch` instruction specially, since it uses a contiguous range of label values. Not all of the labels in the `tableswitch` instruction necessarily appeared in the source code for the program. As a result, some of the branch targets for the cases will be the same as the *default* case target. Therefore, when computing the label set size and density of a `tableswitch` instruction, we ignore all the labels whose branch targets are the same as the *default* case's target.

The figure shows that the average number of labels per switch is 12.8 and that 89% of the switches contain fewer than 30 labels.

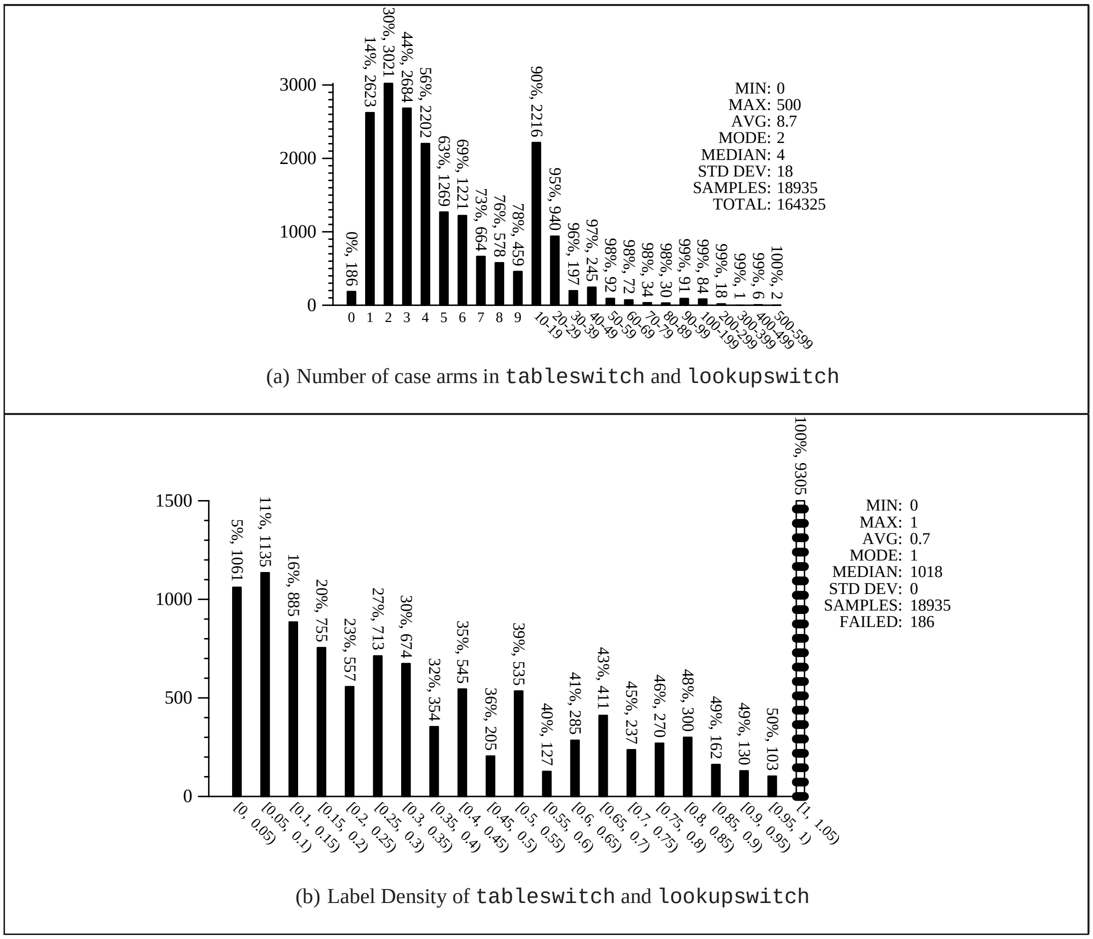
Figure 35(b) shows the density of switch labels, computed as

$$\frac{number\_of\_case\_arms}{max\_label - min\_label + 1} \tag{1}$$

This measure is important for selecting the most appropriate implementation of switch statements [4, 14]. In the JVM the `tableswitch` instruction is used when the density is high and the `lookupswitch` when the density is low.

8 Related Work

In a widely cited empirical study, Knuth conducted an analysis of 440 FORTRAN programs [15]. The study was conducted in an attempt to understand how FORTRAN was actually being used by typical programmers. By understanding how the language was being used a better compiler could be designed. Each of the programs were subjected to static analysis in order to count common constructs such as assignment statements, ifs, gotos, do loops, etc. In addition, dynamic analysis was performed on 25 programs which examined the frequency of the constructs during a single execution of the program. The final analysis studied the effects of various local and global optimizations on the inner loops of 17 programs.



(a) Number of case arms in `tableswitch` and `lookupswitch`

(b) Label Density of `tableswitch` and `lookupswitch`

Figure 35: Switch Statements

Knuth's study was the first attempt to understand how programmers actually wrote programs. Since that initial study many similar explorations have been conducted for a variety of languages. Salvadori et. al [20] and Chevance and Heidet [5] both examined the profile of Cobol programs. Salvadori et. al looked at the static profile of 84 Cobol programs within an industrial environment. In addition to examining the frequency of specific constructs, the authors also studied the development history by recording the number of runs per day and the time interval between the runs. Chevance and Heidet studied the static nature of Cobol programs through the number of occurrences of source level constructs in more than 50 programs. The authors took their study a step further by computing the frequency of the constructs as the program executed. In this study 4 categories of data were examined: constants, variables, expressions, and statements.

Other than Heidet [5], most studies of programmer behavior have concentrated on the static structure of programs. Of equal importance is to examine how programs change over time. Collberg et. al [6] showed how to visualize the evolution of a program by taking snapshots of its development from a CVS repository and presenting this data using a temporal graph-drawing system.

Cook and Lee [10] undertook a static analysis of 264 Pascal programs to gain an understanding of how the language was being used. The analysis was conducted within twelve different contexts, e.g. procedures, then-parts, else-parts, for-loops, etc. Additionally, the authors compared their results with those of other language studies. Cook [9] conducted a static analysis of the instructions used in the system software on the Lilith computer. An analysis of APL programs was conducted by Saal and Weiss [18, 19].

Antonioli and Pilz [2] conducted the first analysis of the Java class file. The goal of their study was to answer 3 questions. (1) What is the size of the typical class file? (2) How is the size of the class file distributed between between its different parts? (3) How are the bytecode instructions used? To answer these questions they examined 6 programs with a total of 4016 unique classes. In contrast to the present study, they examined the size in bytes of each of the 5 parts of a class file (i.e. header, constant, class, field, and method). They also examined instruction frequencies to see what percentage of the instruction set was actually being used. They found that on average only 25% of the instruction set was used by any one program. Our analysis does not focus on the frequency of a particular instruction per program but instead looks at the frequency over all programs. Overall, their study is different from ours in that they were interested in answering a few very specific questions, where our analysis is focused on obtaining a complete understanding of JVM programs.

Gustedt [13] conducted a study of Java programs that measures the tree-width of control-flow graphs. The tree-width is effected by such constructs as `goto` usage, short-circuit evaluation, multiple exits, `break`-statements, `continue`-statements, and returns. The authors examined both Java API packages as well as Java applications obtained through Internet searches.

O'Donoghue, et. al [17] performed an analysis of Java bytecode bigrams. Their analysis was performed on 12 benchmark applications. The only similarity between their data and ours is that we both found `aload_0, getfield` to be the most frequently occurring bigram. We attribute the differences to the small sample size used in their study.

One of the byproducts of our analysis is a large repository of publicly available data on Java programs. Appel [3] maintains a collection of interference graphs which can used in studying graph-coloring algorithms. The availability of such repositories is highly useful in the study of compiler implementation techniques..

9 Discussion and Summary

In this paper we performed a static analysis of 1132 Java programs obtained from the Internet. Through the use of SandMark we were able to analyze the structure of the Java bytecode. Our analysis ranged from simple counts, such as methods per class, instructions per method, and instructions per basic block, to structural metrics like the complexity of control flow graphs.

Our main goal in conducting the study was to use the data in our research on software protection, however we believe this data is useful in a variety of settings. This data could be used in the design of future programming languages and virtual machine instruction sets, as well as in the efficient implementation of compilers.

It would be interesting to perform a similar study of Java source code. Even though Java bytecode contains much of the same information as in the source from which it was compiled, some aspects of the original code are lost. Examples include comments, source code layout, some control-structures (when translated to bytecode, `for`- and `while`-loops may be indistinguishable), some type information (booleans are compiled to JVM integers), etc.

Because of our random sampling of code from the Internet, it is possible that our set of Java jar-files is somewhat skewed. It would be interesting to further validate our results by comparing against a different set of programs, such as standard benchmark programs (for example SpecJVM [1]), or programs collected from standard source code repositories (for example `sourceforge.net`).

We would also welcome studies for other languages. It would be interesting to validate our results by performing a similar study for MSIL, the bytecode generated from C# programs, since MSIL and JVM (and C# and Java) share many common features. It would also be interesting to compare our results to languages very different from Java, such as functional, logic, and procedural languages. It might then be possible to derive a set of “linguistic universals”, programming behaviors that apply across a range of languages. Such information would be invaluable in the design of future programming languages.

Our experimental data and the SandMark tool that was used to collect it can be downloaded from `http://sandmark.cs.arizona.edu/download.html`.

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